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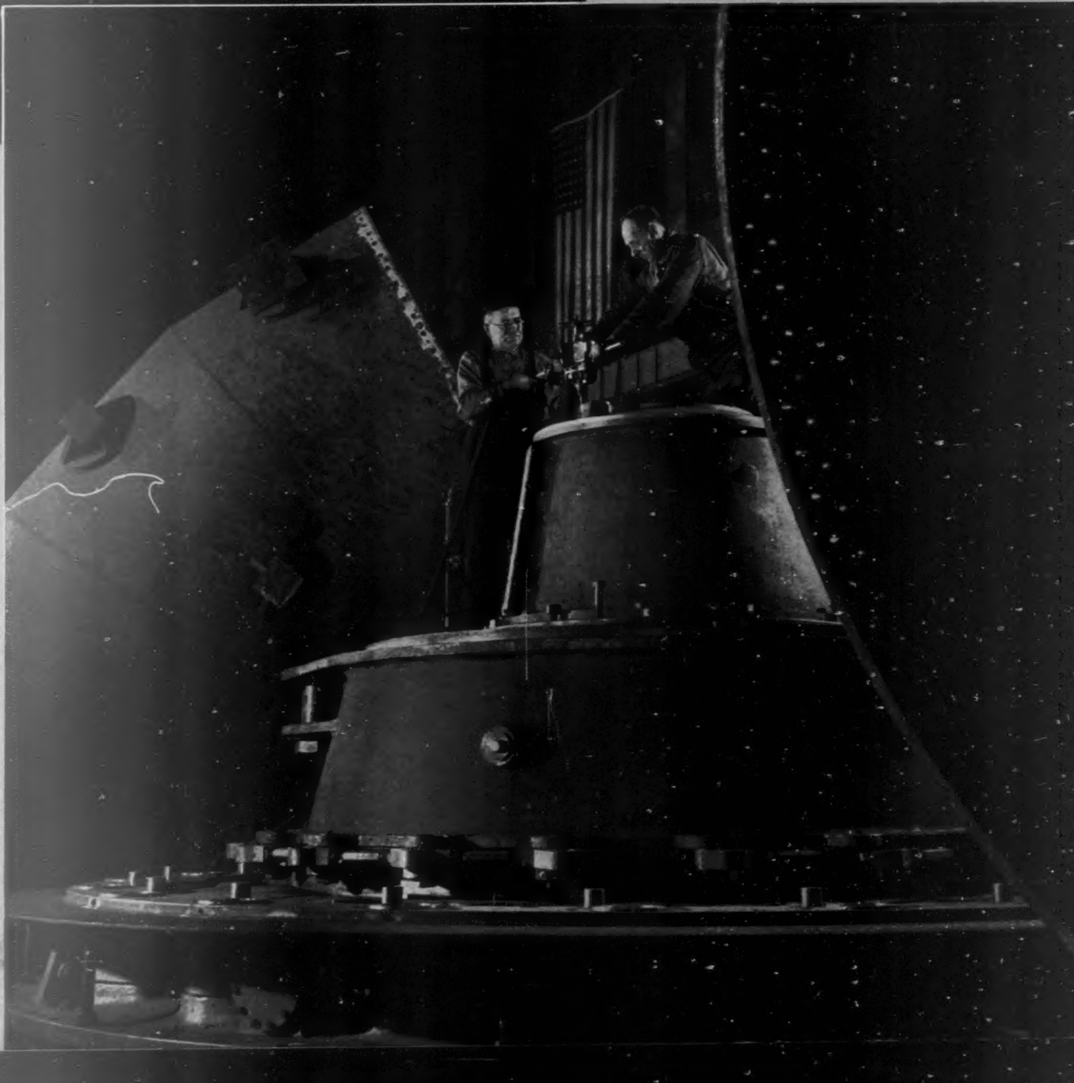
ELECTRICAL REVIEW

March • 1943



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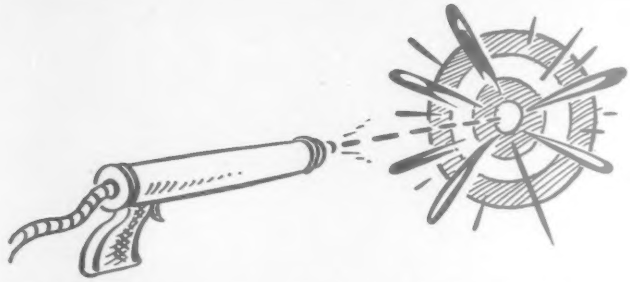

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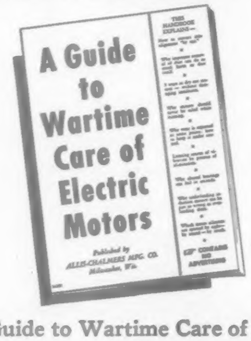

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C O N T E N T S

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BIRTH OF THE OIL CIRCUIT BREAKER

Even when electric power distribution was in its infancy, utility customers took dependability for granted. The little known story of the invention of the oil circuit breaker sheds light on one reason why U. S. industry gets the continuity of service so vital in war.

Dr. Leonard L. Elden **(Retired)**

BOSTON EDISON COMPANY • BOSTON, MASSACHUSETTS

● Little has ever been written of the operating experiences of the early central stations which undertook to supply arc lighting service and later alternating current to their customers. Edison's record of invention, production, and development of the low tension system which bears his name has been spread before the public in great detail. His name has become a byword in every branch of scientific work. Not so conspicuous is the record of the numerous arc lighting companies, who made their debut in the '80s, with generators and related equipment bearing the names of a dozen or more inventors and manufacturers.

In their undertakings, the operating companies, for a time at least, were dependent almost entirely upon the manufacturing companies for the technical advice and assistance which enabled them to meet operating problems encountered in plants. When service for larger centers of population became necessary, the small capacity generators soon proved inadequate, and rapid changes had to be made to meet the increased demands.

Failures of station equipment, storms, floods, wind, sleet, and lightning have always been a threat to continuous operation of power plants, but the public from the first has always taken for granted that dependability is an obligation resting on the operating companies. These companies had problems much like trying to carry water in a paper bag, with destructive elements on every hand threatening to puncture it at critical periods. However, the arc lighting companies met these conditions with reasonable success and continued expansion of their service. Increases in the capacities of their series arc circuits meant the use of larger generators and higher insulation factors in circuits.

Dr. Leonard L. Elden gives an intimate glimpse into the pioneering period in the electrical industry from 1887 to 1900, when he invented the first oil circuit breaker in America.

Born in Buxton, Me., May 16, 1868, and graduated from Quincy (Mass.) high school in 1885, he was employed by Mass. Elec. Pr. Co. the same year. Three years later when this company was absorbed by the Merchants Elec. L. & P. Co., he was placed in charge of electrical station equipment.

In 1888 after another merger formed the Boston Elec. Lt. Co., Mr. Elden was placed in charge of all electrical equipment. He continued in this position until the company was absorbed by Edison Elec. Illuminating Co. of Boston (now Boston Edison Co.), with whom he served as superintendent of the electrical engineering department until he retired in 1932 after 47 years of service.

His contributions to the electrical industry include invention of composite type air circuit breaker, oil circuit breaker and other oil breaker switches.

Dr. Elden was president of the Assn. of Edison Illuminating Co's. in 1918-19 and has served on many committees of the National Elec. Lt. Assn. In 1929 the honorary degree of Doctor of Science was conferred upon him by Tufts College.

Fuses not good enough for a-c generators

The introduction of alternating current generators, belt-driven, in 1887 brought new operating problems to central station operators, who were then unaccustomed to the troubles developed by these new machines under short circuit conditions. The frequent failures of transformers and their protective fusible devices, failures of generator windings and line troubles with resulting short circuits, all increased the hazards of station operation.

The circuit breaker industry was yet in its infancy. Applications that had been made were mostly limited to street railway systems. Some were used in isolated d-c plants, where fuses would not give the desired protection. With one exception no circuit breakers were applied to a-c generators in the next ten years. In spite of many disastrous failures, the manufacturers of a-c generating equipment continued to supply fuses of several types for a-c generator and feeder protection. Fuses were neither dependable nor adequate.

Early a-c generators were single-phase units ranging upward from 500 lights capacity. They were usually separately excited units with single field windings and surface-wound, high-voltage armature windings. The mortality rate for these machines was very high, and improvements were imperative if the service was to become successful.

AT LEFT: For many years superseded by oil, air breakers are once again important. Shown are the insulator columns, which contain interrupting members, of a 1,000,000 kva outdoor air blast unit.

"Composite" type generator

As a-c business developed, the Thompson Houston Co. introduced a new type of generator with a slot-wound armature and compound field windings. This latter feature made the generators self-regulating and improved voltage regulation under changing loads. These "composite" type generators immediately became popular and by 1900 were operating in many central stations throughout the country.

Since the self-regulating characteristics of these generators tended to maintain constant voltage even under heavy overloads, the output of a generator was increased to many times normal during short circuits. Thus short circuits were severe, and frequent failures of belt drives and armature windings were experienced because protective devices then in use were inadequate.

Fuses as regularly supplied by the manufacturers of a-c generators were unreliable. They were too slow in action and, if operative, frequently failed to clear faults. Station operators often cut off the field excitation of these generators to clear trouble when fuse protection failed to function. As larger generators were built and distribution circuits grew, system troubles became more frequent and short circuits more severe and difficult to contend with. Manufacturers of a-c equipment could offer no remedy.

Field breaker developed

The author solved the problem through the development of a circuit breaker designed solely for the protection of composite type generators. This breaker, developed in 1891, comprised a trip coil inserted in the series field winding and opened the series and shunt field windings simultaneously with two knife switches upon occurrence of a predetermined rise in current in the series field winding, such as would occur under heavy overload or short circuit.

This breaker was so effective that a generator could be short circuited at its terminals, and the machine would be killed harmlessly and instantly without perceptible effect on the belt drive. Hundreds of demonstrations of its operation were made without a single failure before interested representatives of other companies. A large demand for the breakers developed almost immediately, and the Boston Electric Light Co. promptly approved the manufacture and sale of the breakers as an accommodation to the industry.

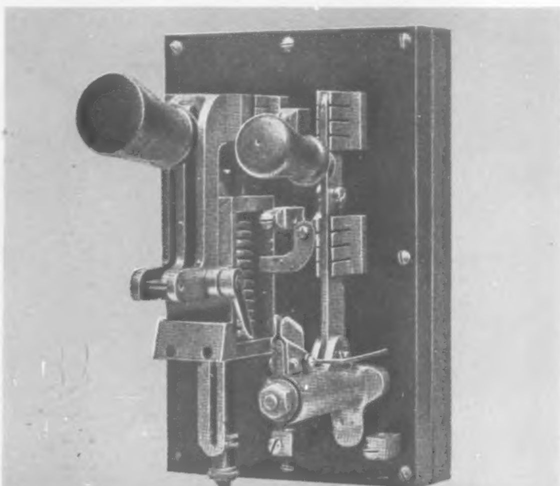


Fig. 1—Composite type oil circuit breaker for alternating current machines invented in 1892.

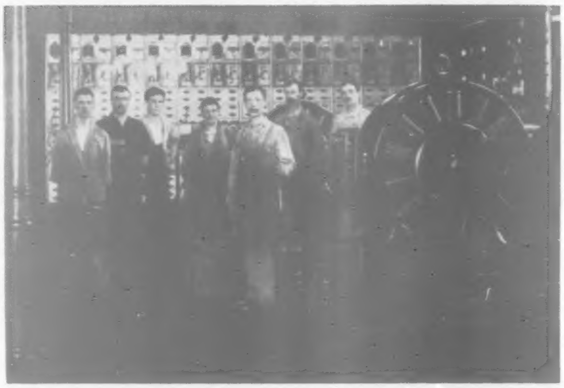


Fig. 2 — Barely discernible in this old photo is the switchboard in the Boston Electric Light Co. plant. Dr. Elden is at extreme right.

As the demand grew for the circuit breakers, it became desirable to arrange for their promotion and sale by an outside interest. At this time S. B. Condit, Jr., became interested in the commercial possibilities of the breakers and finally acquired an exclusive license for their manufacture and sale. With his promotion these breakers became popular wherever composite type generators were used. Later when the "monocyclic" generators were introduced to supply combined lighting and power service, the same protection was successfully applied to that form of generator too.

This form of breaker was applicable to generator protection only for machines of specific types. It was the only circuit breaker ever developed and applied to a-c generator protection before the development of oil circuit breakers for large two- and three-phase a-c generators which came rapidly into use from 1897 onward.

2300 volt air breakers for feeders

For protecting multiple circuits supplied from a single generator, a line of air break circuit breakers was developed by the author for voltages up to 2300. These were also marketed by Mr. Condit. However, the time came when the growth of a-c system capacities required larger and larger generators of different types to meet service demands. Protective devices previously used with small a-c generators were worthless with these larger generators, and the necessity for some new form of protection became apparent.

By 1897 the Boston Electric Light Co.'s a-c generating facilities were operating at near capacity. To meet the increasing demand, construction of a new 9000 kw generating station was authorized. The main generating units were six 1500 kw, 60-cycle, three-phase generators, direct-coupled to vertical cross-compound engines of the most modern type, particularly designed for use with paralleled generators. In addition there were many synchronous motor-generator sets for street lighting service; 60-cycle, 600 volt, rotary con-

verters for d-c power service; and switching equipment for generators, transmission lines, a-c feeders and station auxiliaries. This station was to supersede several of the company's older, uneconomical stations and later to become the principal source of energy for the company's entire system.

No switches available for 9000 kw plant

Direct-connected, steam-driven generators of this size had not yet been successfully paralleled. Adequate switching equipment for a system of such a large capacity was lacking. As a result of the high overload rating of the generating units and their low reactance, the short circuit output of the combined plant could easily reach 200,000 kva. This exceeded the possible output of any steam plant then in operation and involved an operating duty on switches and circuit breakers not previously experienced. A survey of the products of the largest manufacturers of a-c apparatus revealed only two switching devices that might have been applicable to such heavy-duty service.

One proposed unit had large air break switches with arms five feet long, designed to handle large-capacity generators and transmission lines. When opened under load, these breakers drew tremendous arcs which frequently rose to the roof of the station building. In a New York street railway station, the breakers were mounted high on the station wall over the main switchboard. A separate building housed one of these switches at Niagara Falls, where it controlled a heavily loaded transmission line. Its ability to open the line under load was questionable, and the generator was shut down when such operation was necessary.

Another manufacturer experimented with a different form of air break switch, but it failed when subjected to tests with very limited generator capacity. This switch had a set of wooden tubs enclosing fixed contacts for each pole of a three-phase circuit. Movable contact rods, passing through the tops of the tubs, provided means to close or open the circuit within the tubs. Any arc formed by opening the circuit was expected to be extinguished in the air inside the tubs to break the circuit without danger of an arc spreading to nearby structures.

Bus transfer switch experiments

Early in 1898, when contracts were awarded for the complete equipment for the Boston Electric Light Co.'s new generating plant and sub-stations, neither manufacturer was willing nor able to offer switching or circuit breaking equipment which could be guaranteed for the service. Thus it became necessary for the Boston Electric Light Co. to seek a solution of this problem elsewhere.

For several years the author had been experimenting with various forms of switching devices then available on the market, trying to get bus transfer switches suitable for switching heavy a-c feeders from bus to bus. As feeders grew in capacity, much trouble had been experienced when such transfers were made under load.

One switch tested was an air break switch equipped with tubular porcelain insulators to enclose the live contacts and confine any arcs which developed when a circuit was broken. Another switch was equipped with shutters, arranged to enclose quickly the stationary live contacts when the switch blades were withdrawn and thus snuff out any arcs that might develop. These switches were erratic in performance, and in the end they were found entirely unsuited for heavy-duty service.

It was felt that this switch problem had to be solved to insure success in the company's future operations. Studies were made of every possible construction which seemed likely to accomplish results. Much of the effort was without tangible results, but the use of oil as an arc quenching medium in switches seemed to have merit. It seems odd that such a simple solution of a-c switching troubles, as the use of oil later proved to be, could have been so long overlooked, for it already had many other uses in the electrical industry.

Oil on brushes reduces arcing

Each of the Thompson Houston arc lighting generators was equipped with a blower mounted on the shaft for delivering a blast of air on the commutator in front of the tips of certain brushes where arcs regularly formed. Oil drawn into the blower from the lubrication system was ejected on the commutator surface by the air jets, and it seemed to control the length of the arcs at the brush tips. Furthermore, carbon brushes soaked in oil or impregnated with lubricating materials sparked less on the commutators of d-c machines than non-lubricated brushes.

"Do these conditions in any way indicate usefulness of oil as an arc-quenching medium in switching apparatus?" We often wondered.

A more important use of oil had been made in oil-filled transformers, which had become a standard product of all transformer manufacturers by this time. Oil served as a high-grade insulator and cooling medium. A study of this use of oil and of the operating records of transformers furnished a firm basis

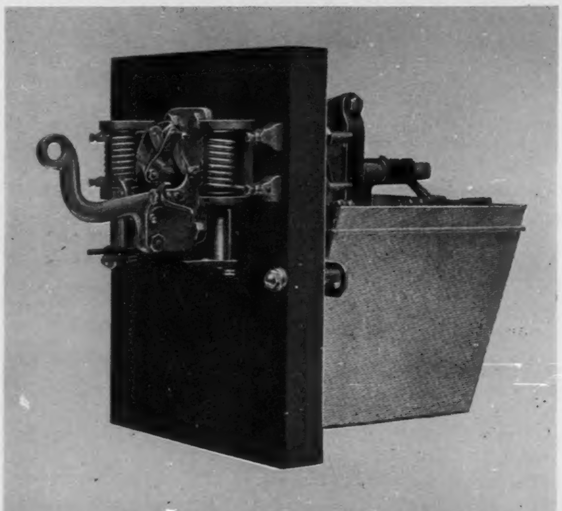


Fig. 3—Oil circuit breaker developed in 1896 for the Boston Electric Light Company's "L" Street Station.

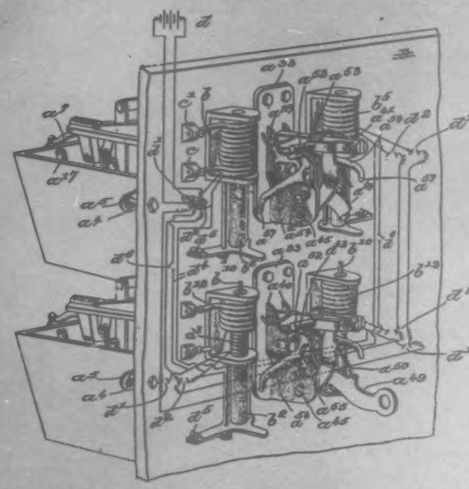


Fig. 4—Illustration from patent covering oil circuit breaker.

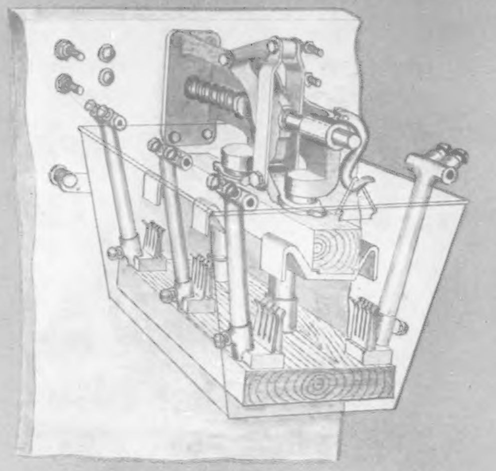


Fig. 5—Interior of early oil circuit breaker shown in Fig. 3.

for expecting success in its use in switching apparatus for a-c systems.

Oil quenched transformer arcs

The operating record of oil-filled transformers showed that winding insulation might break down, permitting flashover to the core, but arcing to the case from immersed coils or leads was unknown. Arcing to the case was always from live connections on terminal boards or coil leads above the oil level. Immersion of terminal boards and coil leads and placing of adequate insulation on all remaining exposed live parts within transformer cases eliminated this type of trouble.

It thus appeared that oil in transformers was an insulating medium which prevented the development of arcs and also a quenching medium which tended to interrupt any arc that might develop under abnormal voltage.

The first experiment in the use of oil in switches was made in 1897 with a 6.6 ampere d-c series street lighting circuit. This circuit was opened under oil but without satisfactory results because the arc produced considerable disturbance in the oil. This effect proved to be the result of the automatic regulating feature of the generator, which increased the circuit voltage in an attempt to maintain constant line current as the arc resistance increased. A second test of this circuit with the generator regulator blocked was more promising, but the results still were not satisfactory.

Oil switch on station bus

Next, one side of a 2300 volt, single-phase lighting circuit, supplying the station lighting load and a test bank of about 1000 lamps was routed through the oil vessel and then opened repeatedly under oil without any disturbance or semblance of an arc.

Larger loads were added, and finally the load of a 120 kw generator operating at capacity was repeatedly opened with equal success. This was the largest a-c generator operated by the company at that period. All tests made consisted of opening a loaded line, but in no case under short circuit conditions. Such tests came later. All of the a-c generators then in use were of the composite type and were fully protected with automatic circuit breakers as described before.

After tests had demonstrated the adequacy of oil as a rupturing medium, a complete oil switch was built and mounted in an iron box. Further studies were then made of the possibility of adapting such switches for use as bus transfer switches in the a-c system. This switch was later converted into a circuit breaker and placed in regular service on a new 150 kw, three-phase, 2300 volt generator which was purchased late in 1897 for experimental purposes. Then the switch was subjected to short circuit tests which fully established its value as a protective device on the largest generator operated by the company.

New plant equipped with oil switches

The success of the experimental oil circuit breaker led the author to develop oil switches and circuit breakers suitable for use in the Boston Electric Light Co.'s new generating plant and substations then under construction. This was a serious undertaking, and many predictions of failure were made by engineers and others interested in central station operations. However, when the new generating station (L Street Station) was put into operation late in 1898, suitable oil switches and circuit breakers had been developed and manufactured.

By the middle of 1899 the station was in full operation, and both the station and the system had been fully equipped with oil circuit breaking devices. Switching equipment for the generating station included heavy-duty, pneumatically operated generator switches; double-throw transfer switches; circuit breakers for synchronous arc-lighting motor-generator sets; and switches and circuit breakers for transmission lines, a-c feeders and station auxiliaries. Similar

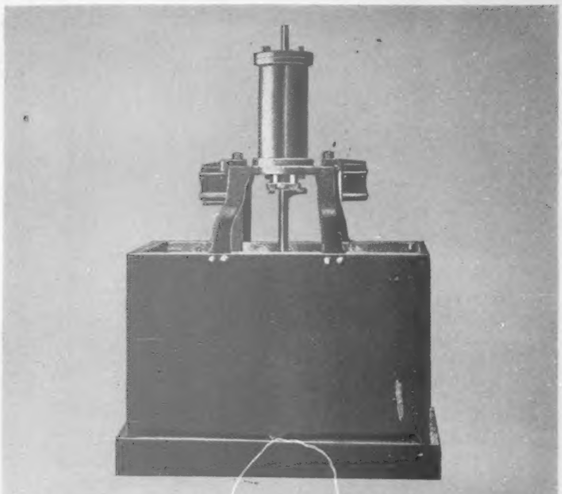


Fig. 6—Pneumatically operated generator oil circuit breaker opened and closed by manually operated valve.

switching devices as required were installed in substations.

This was the first central station system in the United States (or elsewhere so far as is known) to be completely equipped with oil circuit breaking devices. Their successful operation under service conditions attracted wide interest, and an immediate demand developed for all types of oil switches and circuit breakers used.

There is no record of any other attempt in the United States to develop circuit breakers or switches using oil as an interrupting medium until about the middle of 1898. At that time, in a New York power station, oil was introduced into the arcing chambers of an air break switch which had previously failed to handle successfully the output of a generator of moderate capacity. The results of these and other experiments led to the development of the live-tank oil circuit breaker which was offered to the industry in 1899.

Condit markets new switches

Again the company passed its experience on to the central station industry by making these oil type products available. The success attained by Mr. Condit in promoting circuit breakers for composite generators made him the logical man for marketing the newer oil breakers and switches. His success with this new product, through the company formed under his own name, speaks for itself; for in the following years many plants in New England and other sections of the country chose his products.

Additional oil switching devices, designed by the author, were produced in 1900-1901 by the Condit Co. These included a "rotary oil type transfer switch," designed to transfer single-phase loads to the different phases of a three-phase system to maintain balanced load conditions. A remote-controlled solenoid operating an oil switch and circuit breaker was the first application of solenoid operation. These special devices were used extensively in smaller stations where load conditions were harder to control.

The author applied for and was granted a patent (No. 756,344) on oil switches. The patent application was filed a long time before it issued in 1904, but interference proceedings involving an electrical equipment manufacturer were long drawn out. The application claimed as the invention an oil circuit breaker utilizing oil as an interrupting means for electric arcs and cited reduction to practice in the station of the Boston Electric Light Co. in 1897.

Hammer loosens sticky breakers

Early use of standard air break type circuit breakers on 600 volt d-c power circuits showed that many failures to open under service conditions were caused by sticking contacts. To overcome this fault, the author in 1896 developed an air type breaker with an auxiliary weighted handle which delivered a heavy hammer blow to the regular operating lever when released by the trip coil. The hammer blow, combined with the action of the regular spring mechanism, insured the quick opening of the breaker. These d-c breakers were sold by the Condit Co. in large volume for all forms of d-c service up to 600 volts.

This article is confined to a cycle of about seventeen of the earliest years of central station activity in the United States. Starting in 1882, the arc-lighting and low-tension d-c systems held sway in their respective fields. By 1887 a-c systems entered the field and in the next twelve years made progress toward their ultimate domination of the electric power field. It was in the last three years of this period that demands for improved switching equipment for a-c service brought about the substitution of oil switches for air break switches.

Next, greatly increased generator and system capacities necessitated the design of oil switches of higher ratings to meet these new conditions. From then on, through forty years, it has been a continuous struggle for switch manufacturers to keep pace with system capacities. Air gave way to oil in the early days, but now air break switches and breakers are in competition again with oil.

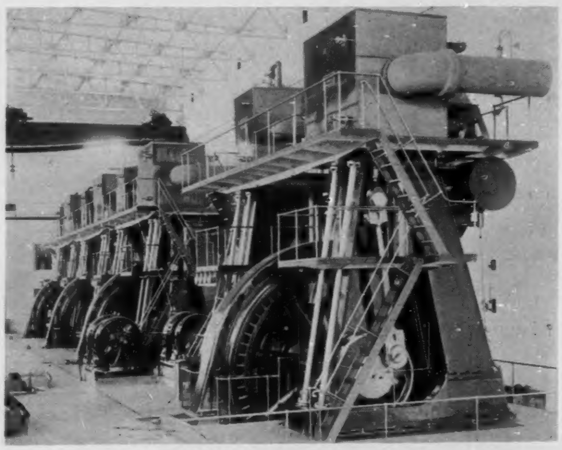


Fig. 7 — Four of six 1500 kw a-c generators installed in Boston Electric Light Co.'s "L" Street station, built in 1898-99.

LANDMARKS IN OIL CIRCUIT BREAKER DEVELOPMENT

From Dr. Elden's first 400 ampere, 4 kv breaker to the 4000 ampere, 230 kv giants of today is a long hop. Yet many of the fundamental features in that first unit are still used to handle wartime's tremendous loads.

K. B. Seely

SWITCHGEAR DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

● In this issue, Dr. Elden describes the experiments which led to the development of the first oil circuit breaker in America in 1897-98. At that time the Boston Electric Light Co. was building its new L Street station in South Boston, and Dr. Elden as chief operating engineer had to find adequate switching facilities.

Dr. Elden soon learned that existing protective equipment could not handle the loads, and he developed oil circuit breakers suitable for use in the new generating plant and substations. His contemporaries predicted failure and some authorities even reproached the Boston Electric Light Co. for entrusting such a project to an untrained engineer, not realizing that Dr. Elden had thirteen years of power-house experience. However, when the new generating station was completed late in 1898, the necessary oil switches and circuit breakers were ready for installation.

First testing generator

Contributing to his success were his facilities for predetermining the performance of his circuit breakers by short circuit tests. The 150 kw, three-phase generator installed in 1897 for experimental purposes was probably the first circuit breaker testing generator.

Sears B. Condit, Jr., who arranged in 1892 to manufacture and sell Dr. Elden's air circuit breakers, was in close touch with him during the development of the oil switches. Mr. Condit formed a company in 1899 under his own name, and in 1900 it was licensed to manufacture and sell both air and oil circuit breakers.

The first commercial oil circuit breaker developed in America is illustrated in Fig. 3 of Dr. Elden's article. The manually operated type "A" breaker, as it was called, was rated 400 amperes, 4000 volts, arranged for mounting on the rear of a switchboard panel. The electrically operated unit (Fig. 2) was developed in 1899, and it is now in Henry Ford's museum at Dearborn, Mich.

Features still popular

At first glance the type "A" breaker appears to be nothing more than an up-break knife switch immersed in a bucket of oil. However, some of its principles are used in the most modern oil circuit breakers:

(a) Both the stationary and movable conductors were rigidly supported near the point of contact to avoid difficulties from electro-magnetic forces produced between the conductors by high currents. The conductors form a ¾ turn coil, and current flowing downward in one stud and upward in the other causes a concentration of magnetic forces inside the coil. This creates a repulsive force between the conductors, which tends to force the conductors apart and to bend them into a circular shape.

(b) The knife-blade and jaw contacts, besides giving firm contact pressure, provided two parallel paths to conduct current in the same direction to the blade. Thus the eternal magnetic field, particularly at high currents, would force the jaws together, tending to offset the "throw-off" effect. When the contacts of a circuit breaker are closing, they first make contact at only one point. Current flowing in opposite directions to and from the point of contact causes magnetic repelling forces to separate the contacts momentarily. Unless the contacts are correctly designed, the consequent arc may weld the contacts together upon completion of the closing stroke.

(c) A wooden cover, in addition to protecting the

AT LEFT: Cooling and mixing molten iron in the gray metal foundry of a midwestern fabricating plant prior to pouring.

Fig. 1 — Installed in 1899, pneumatically-operated, single-pole, 1500 ampere, this 3000 volt breaker remained in service until 1941.

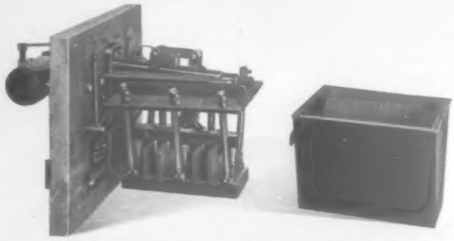


Fig. 2 — Type "A" breaker with solenoid for electrical operation is now in Henry Ford's museum at Dearborn, Mich.

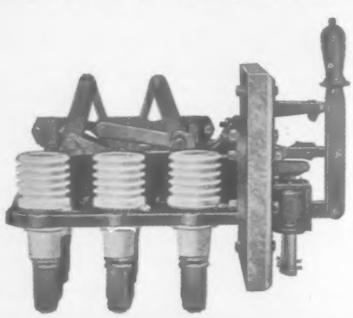


Fig. 3 — Type "C" automatic trip, manually operated unit had a fiber tank, trip-free mechanism, a metal cover.

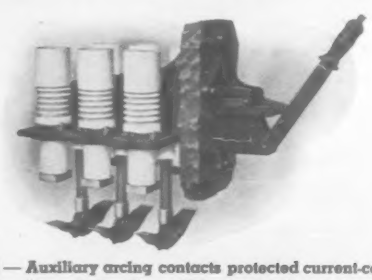


Fig. 4 — Auxiliary arcing contacts protected current-carrying brushes of the Type "D" three-pole oil breaker.

oil from dust, limited oil throw and supplied a secondary support for the conductors.

(d) Straight line motion of the movable member was insured by two guide rods extending upwards from the wooden base on which stationary contacts were mounted.

(e) The operating mechanism had a toggle linkage so arranged that it was on or slightly over-center with the breaker closed. An impulse applied to the midpoint of the toggle would trip the breaker by forcing the toggle off-center and allowing the contacts to be opened by pressure from springs which had been compressed during closing. Toggles are still widely used in oil circuit breakers.

(f) The tripping impulse was applied by a trip coil. This was either a series type, with consequent high voltage on the front of the switchboard, or one operated from a current transformer.

Oil breakers distrusted

An early catalog explains the hooked operating handle shown in Fig. 3 of Dr. Elden's article:

> "As it is the general practice to locate circuit breakers at the top of switchboards and usually out of reach, we have designed the type illustrated to be operated by a portable handle with a suitable hook at the end. When, however, the breaker is located within reach, a fixed ornamental insulated handle is substituted for the one shown."

The catalogue was issued about 1900 when oil circuit breakers had been operating successfully for two years at the Boston Electric Light Co. plant. Engineers apparently were still lukewarm to the new interrupting means, as indicated by further extracts:

> "The introduction of a-c apparatus for general use in central stations was followed by numerous accidents and interruptions to the service supplied, largely due to the unsuitable protective and switching devices used.
>
> "A study of the various methods used in fairly recent installations shows devices having breaks up to several feet in length with large barriers between individual lines to prevent arcing between them.
>
> "Another method is the employment of fuse-shunted switches or circuit breakers which depend on the efficiency of the fuses for their reliability. In some stations we see the attendant waving a long pole, having a contact on the end which normally is inserted in a receptacle high up on the wall, but which is removed and waved around in the air to break the arc when it is desired to interrupt that particular line. That these methods fail at critical moments is a well known fact, and if the inner history of many stations operating large units was laid bare, it would show many such failures."

Pneumatic switch

Along with the oil circuit breaker, a pneumatically operated switch, shown in Fig. 1, was developed.

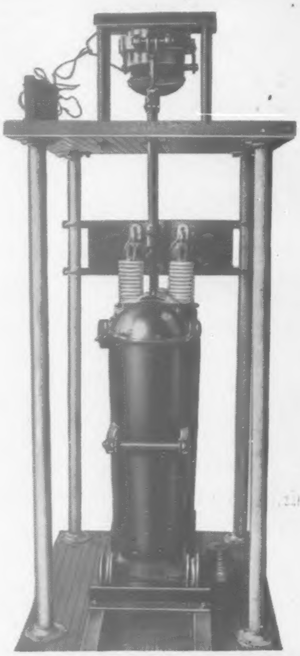


Fig. 5a — First truck type breaker, Type "F," had primary disconnects.

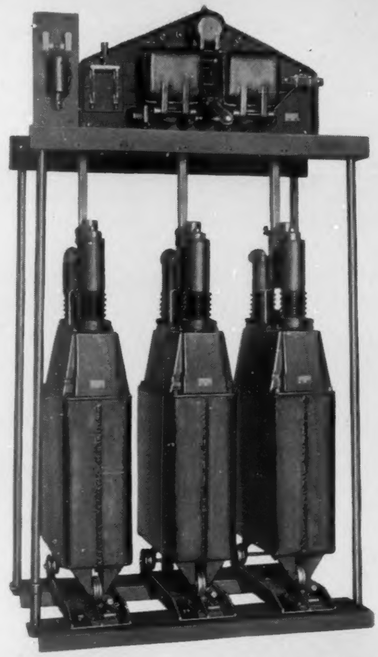


Fig. 5b — The three poles of the improved Type "F" breaker were operated from two solenoids.

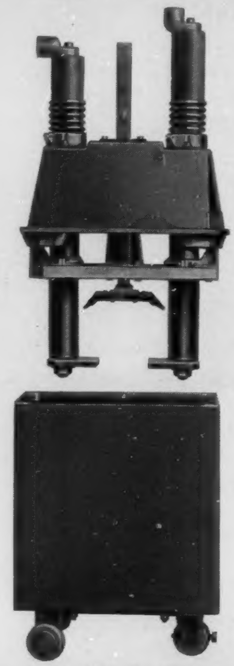


Fig. 5c — Improved Type "F" had up-break laminated brushes.

"Pneumatic operation for this heavy-duty oil switch was chosen," explained Dr. Elden, "because the use of air for our switches seemed the easiest way to get fast and reliable operation."

This pneumatic switch was rated 1500 amperes at 3000 volts, and it was offered for single-, two- and three-phase service. It was designed for 40 to 50 pounds air pressure but was adaptable to other pressures. Operating valves were opened and closed by hand or by solenoids with push-button control. The contact construction was similar to that of the type "A" manual oil circuit breaker.

This switch was far ahead of its time because pneumatic operation of oil circuit breakers has only recently been gaining acceptance. One of these breakers (Fig. 1), installed in 1899, was in operation until 1941.

The oil used in these breakers was not the low viscosity oil in general use today, but rather a heavy oil of high viscosity, selected to reduce splashing caused by the movable member. During operation oil tended to leak through the holes in the cover through which the lift rods passed.

Cast metal covers

In about 1903 the breaker shown in Fig. 3 incorporated a number of improvements based upon the operating and manufacturing experience gained from the original types of breakers. The new type "C" breaker was rated 200 amperes at 15,000 volts, and the removable wooden cover had been superseded by a sturdy ribbed metal casting which gave a rigid foundation for the mechanical and current-carrying parts. Later years proved the necessity of rigidity to assure proper operation and alignment of movable members during heavy faults. This general construction of circuit breakers has been followed up to the present day.

Another improvement in the type "C" breaker was the individual fibre tank for each pole. Later a fibre-lined metal tank was developed.

The operating mechanism of this breaker included a trip-free linkage which made it impossible to hold the breaker closed when a trip coil was energized by an overcurrent in the line. A downbreak form of contact construction was used because it utilized gravity for accelerating the movable member during opening and for breaking the circuit if the lift rod failed. The unit also had a form of plunger type contacts which were later discarded, only to be recently adopted again in an improved form.

Laminated brushes

Further experience proved the need for efficient current-carrying contacts separate from contacts used for interrupting the circuit. The laminated brush was adopted from air circuit breakers in 1903 for the oil breaker shown in Fig. 4. This type "D" breaker was

built for 200 amperes at 15,000 volts and up to 1200 amperes at 3300 volts.

The introduction of the laminated brush accompanied the separation of the interrupting function from the current-carrying function. The brushes were coordinated with easily renewable, auxiliary arcing contacts, arranged to make contact before the brushes did during closing and break contact after the brushes during opening. Thus arcing was confined to the arcing contacts, thereby keeping the brushes in good condition for carrying current. A group of type "D" breakers installed in about 1903 remained in service until replaced by breakers of modern design in 1941.

By 1909 the power handled in generating plants and substations had increased considerably, and the phase-per-tank circuit breakers which had been developed were too heavy for mounting on switchboards. Consequently the type "F" breaker (Fig. 5a) was designed for cell mounting equipped with wheels and primary disconnects. The operating mechanism was separately mounted so that the oil circuit breaker could be withdrawn for inspection or repair without disturbing the control connections.

This truck type breaker was a forward step because inspection and repairs were simplified and a high cell was not necessary to permit tank removal. As was to be expected, the higher capacity breaker required a more powerful operating device, and a clapper type of solenoid was developed.

Up-break contacts

A later form of type "F" breaker, arranged for three-pole operation from two solenoids, is shown in Figs. 5b and 5c. It was rated 1000 amperes at 6600 volts and had "up-break" contact construction. The advantage of up-break construction for high capacity breakers is that heavy currents cause a concentration of magnetic force within the U-shaped circuit which forces the inverted brushes against the stationary contact blocks. This improves the current-carrying capacity of the structure by lessening contact resistance.

An inherent advantage of the use of laminated brush contacts is shown in Fig. 5c. When the contacts are separated, the ends of the laminae are in an inclined plane with respect to the stationary contact surfaces. As the brushes are forced against the horizontal stationary contact bars, a wiping action scrapes off copper or oil oxides which might increase the contact resistance and cause heating. The springiness of the laminae assists in accelerating the moving parts at the beginning of the opening stroke.

In 1910 a high tension type "R" outdoor breaker (Fig. 6) was introduced. This 70 kv breaker had dry type porcelain bushings and a horizontal rotary break. It was installed in the state of Washington.

Double-circuit breaker

A heavy-duty oil circuit breaker (Fig. 7) was developed in 1914, designated type "Y" and rated 5000 amperes at 2500 volts. In this breaker the problem of providing the necessary current-carrying capacity and proper insulation was solved by making two parallel circuits for each phase and a separate tank for each circuit.

In most circuit breakers a round stud passing through a porcelain insulator carries the current. In this case, three flat bars passed through an opening in the tank top, and adequate air clearance was pro-

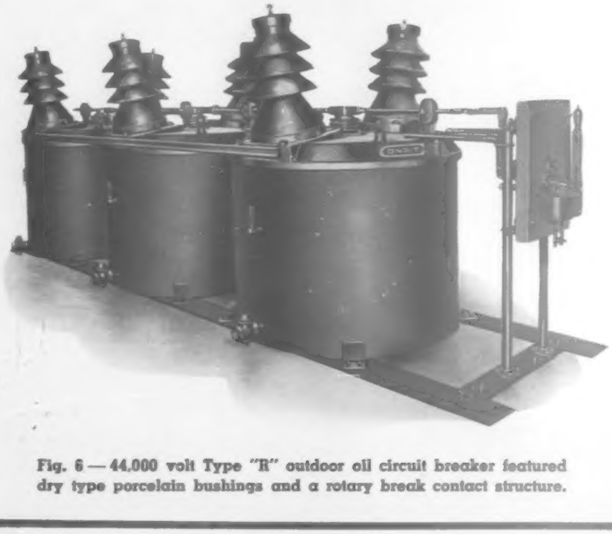


Fig. 6 — 44,000 volt Type "R" outdoor oil circuit breaker featured dry type porcelain bushings and a rotary break contact structure.

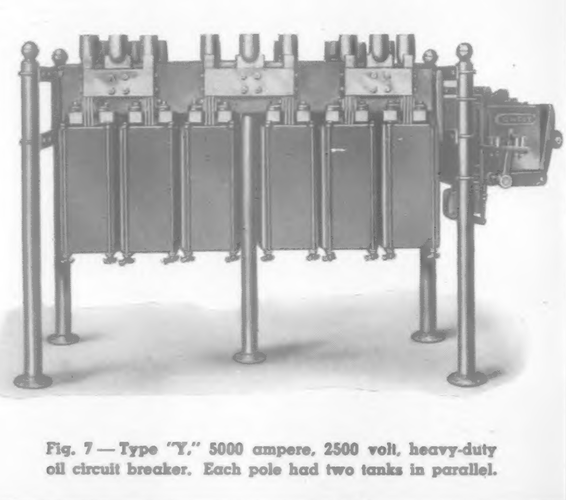


Fig. 7 — Type "Y," 5000 ampere, 2500 volt, heavy-duty oil circuit breaker. Each pole had two tanks in parallel.

vided. The bars were supported by clamps mounted on porcelain insulators resting on the top frame. Upbreak contact construction was used, and the contacts consisted of two brushes mounted at an angle of 45 deg to matched V-shaped blocks on bottoms of the studs. Each phase had solder type lugs for three cables.

An outdoor oil circuit breaker, known as type "D-16" (Fig. 8), was built in 1918 for 300 ampere, 44 kv service. Down-break contact construction was used again, and the tanks had ends rounded to give greater strength than possible with a rectangular tank.

AIEE creates standards

Electrical energy consumption nearly tripled from 1915 to 1920. As the number and size of generating units increased, oil circuit breaker troubles revealed that interruption of heavy currents under oil was not as simple as at first thought.

A paper, presented before AIEE by G. A. Burnham, E. M. Hewlett and J. N. Mahoney in 1918, dealt with the rating and selection of oil circuit breakers. The need for some form of standard was pointed out.

The Electric Power Club adopted in 1919 the CO-2 minute-OCO duty cycle which specified that a breaker should interrupt its maximum rating on this duty cycle. No restrictions were placed on the performance, other than that the breaker should interrupt its rating "and then be in condition to be closed and carry rated current." Flame and oil throwing were permissible so long as they did not interfere with the performance of the duty cycle.

The heavier duty requirements led to the development of the type "D-17" breaker (Fig. 9a) with an energy absorption feature intended to eliminate flame

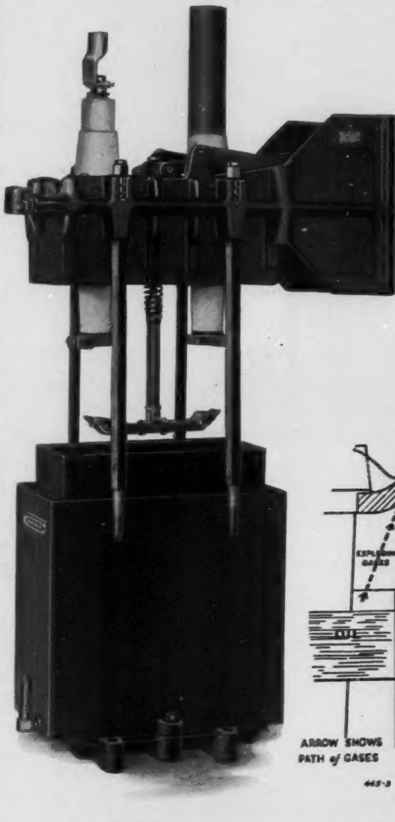


Fig. 9a — Type "D-17," three-pole 600 ampere, 15,000 volt breaker with energy absorption feature.

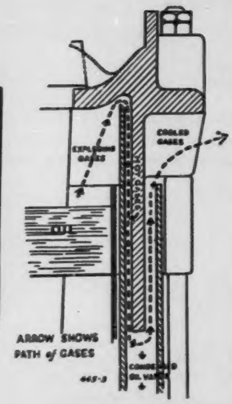


Fig. 9b — Path of gases created by interruption in double-tank breaker.

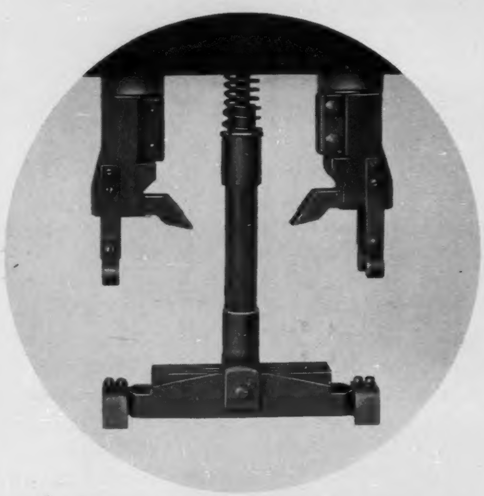


Fig. 9c — Inverted brush arrangement, plus wedge and finger contacts, improved contact during heavy fault currents.

Fig. 8 — Note strong tank with rounded ends on Type "D-16," 300 ampere, 44,000 volt, outdoor oil circuit breaker.

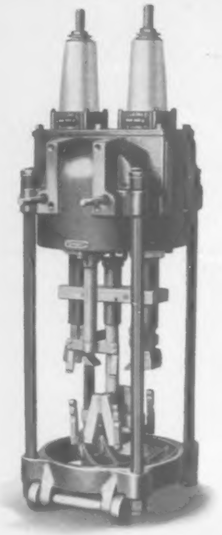


Fig. 10 (at left) — Type "F-8," 600 ampere, 15,000 volt, electrically operated oil circuit breaker had four breaks.

Fig. 11 (at right) — Also having four-break contact structure — the double-tank Type "F-9," rated 600 to 2000 amperes, 15,000 volts.

and oil throw. Two tanks enclosed each pole, an inner and outer tank so arranged that a long, deep flange on the top frame extended down between them (Fig. 9b). The inner tank was suspended on springs. This construction absorbed much of the shock caused by expansion of the gases produced during interruption and provided a restricted passage for cooling and condensing the hot gases during their passage to the atmosphere. Condensed oil was collected in the outer tank. This feature was the forerunner of the oil and gas separators of today.

Contacts that tighten

The type "D-17" breakers were rated from 500 to 1200 amperes and 15 to 25 kv. Interrupting capacity was approximately 115,000 kva. They were followed by the types "D-17A" for 400 and 600 amperes and "D-17B" for 800, 1200, and 1600 amperes. The latter had a form of inverted brush (Fig. 9c) to offset the electro-magnetic forces occurring during heavy fault currents. The breaker incorporated wedge and finger type arcing contacts which tighten when high currents flow, just as the knife and jaw contacts of the type "A" breaker.

Within two years after the development of the energy absorption principle, a multiple-break type "F-8" circuit breaker (Fig. 10) was introduced. It was built in ratings of 600 to 2000 amperes for 15 kv and had an interrupting capacity of 520,000 kva. Four breaks in series had the effect of splitting up the arc into a number of smaller arcs. As the total break distance increased in proportion to the number of breaks, the effective speed of contact separation was greatly increased. Total heat absorption by the contacts was also multiplied. The net effect was a considerable increase in interrupting efficiency.

The next development was a breaker combining both energy absorption and the multiple break features. This type "F-9" breaker (Fig. 11a) had an inner tank supported by a heavy helical spring resting on the bottom of the outer tank. The breakers were built in current ratings from 600 to 2000 amperes at 15 kv, and the interrupting capacity was 780,000 kva. Finger and wedge type arcing contacts helped increase the interrupting capacity.

Old standards obsolete

By October, 1924, the electrical power industry had developed to such an extent that the 1919 duty cycle was obsolete. A new standard was adopted, the OCO-2 minute-OCO duty cycle, which banned flame-throwing, but not oil-throwing. Furthermore, the standard required that, after the specified duty, the breaker should be "in substantially the same mechanical condition as before." The electrical condition specification required that "after performance at or near its interrupting rating, the interrupting ability of the breaker may be materially reduced, and it is not to be inferred that it may be reclosed after such performance without inspecting and, if necessary, making repairs."

Blowout coils

Within three years after the adoption of the new standard the type "D-121" breaker (Fig. 12a) was introduced. Current ratings were from 400 to 1200 amperes, and the interrupting capacity was 120,000 kva. The $1\frac{1}{4}$-turn magnetic blowout coils (Fig. 12b) introduced into the movable arcing contact circuit created a magnetic field which forced the arc at each

Fig. 12a — Type "D-121," three-pole, 600 ampere, 15,000 volt oil circuit breaker with magnetic blowout coils.

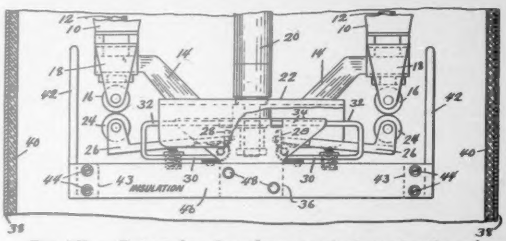
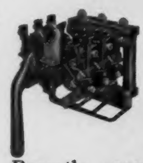


Fig. 12b — Patent drawing shows contact construction of "D-121" breaker and operation of magnetic blowout coils.

contact outward into the oil. As the magnetic field increased in proportion to the short circuit current, the effect of the magnetic blowout increased. Test records show interruptions with arc durations of ½ cycle at currents of 18,000 amperes with a four-break circuit breaker.

The introduction of the magnetic loop breaker closed the pioneering period in oil circuit breaker development. Oil circuit breaker development had been based largely upon experience gained in the field, and the operating companies that cooperated in furnishing information on breaker performance deserve recognition. Since that time most circuit breaker manufacturers have had interrupting test facilities which enabled them to forecast accurately the performance of new designs under actual operating conditions.

New Equipment

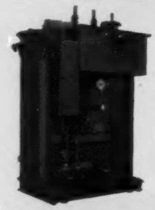


Complete Line of Control Equipment

Recently announced is a complete line of control assemblies and devices for providing improved operation of practically any power application. In addition to specially engineered assemblies, following are some devices carried in stock:

D-c and a-c magnetic (one to four pole) and electro-pneumatic contactors; cam-operated switches (illustrated), single and double throw, 30 amperes and up; rotary switches, up to 12-position; push-button switches, single or multiple circuit, spring return or push-pull type, up to 30 amperes.

Relays — current, voltage, power directional, reverse current, time delay, instantaneous and thermal overload types; electro-pneumatic valves; a-c and d-c solenoids and magnets, small torque motors, air cylinders, drum switches and controllers, battery charging equipment, position control and indicating systems, small high interrupting capacity switches, etc.



Improved Furnace Transformer Tap Changer

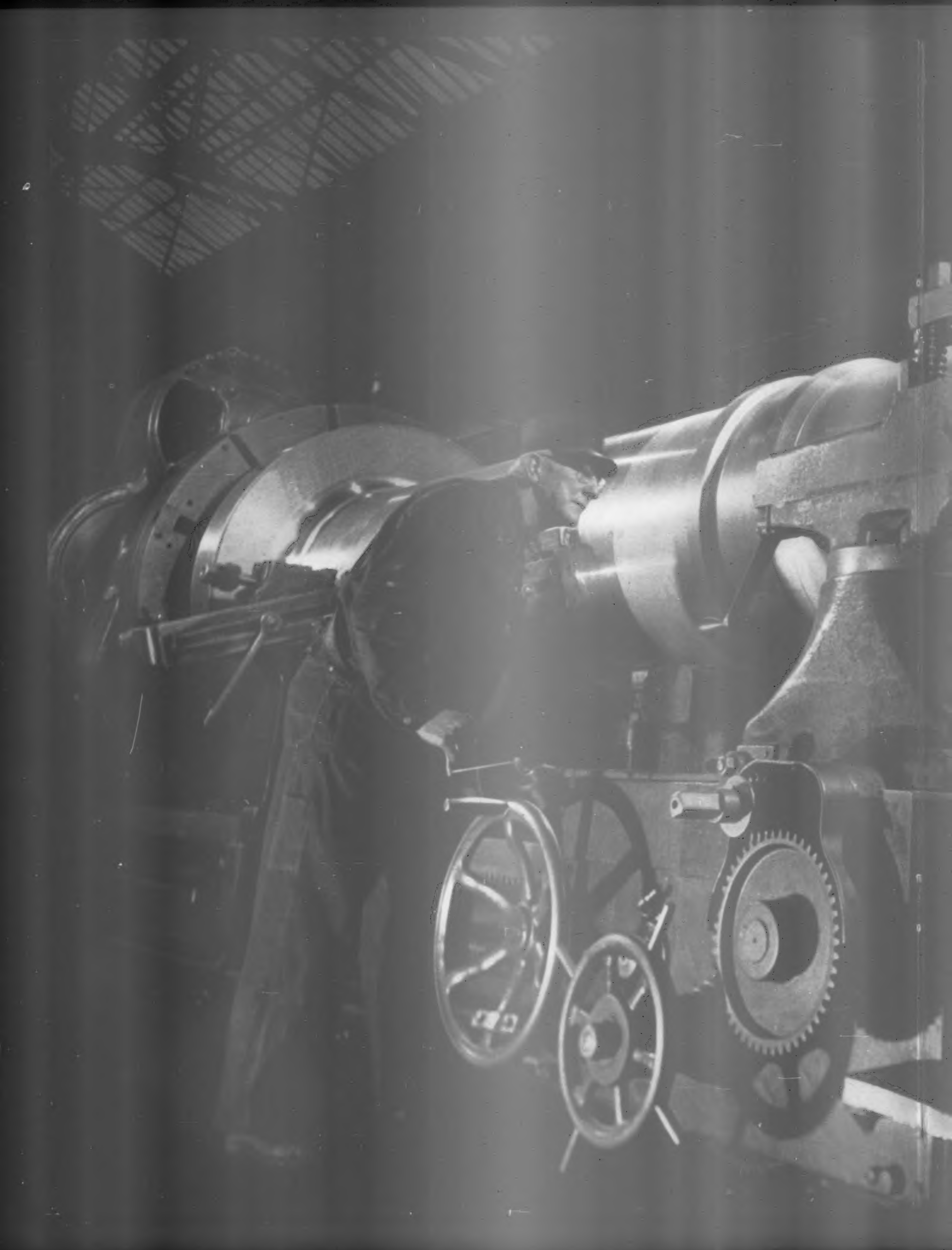
Electric furnace transformers are being heavily overloaded in an effort to increase vitally needed steel. In order to provide a means of quick inspection, replacement, and repair, if necessary, the tap chamber is now located in an offset compartment from the main transformer tank. This compartment has its own cover which makes it possible to inspect and remove the complete tap changer assembly without disturbing the main transformer cover or transformer assembly.

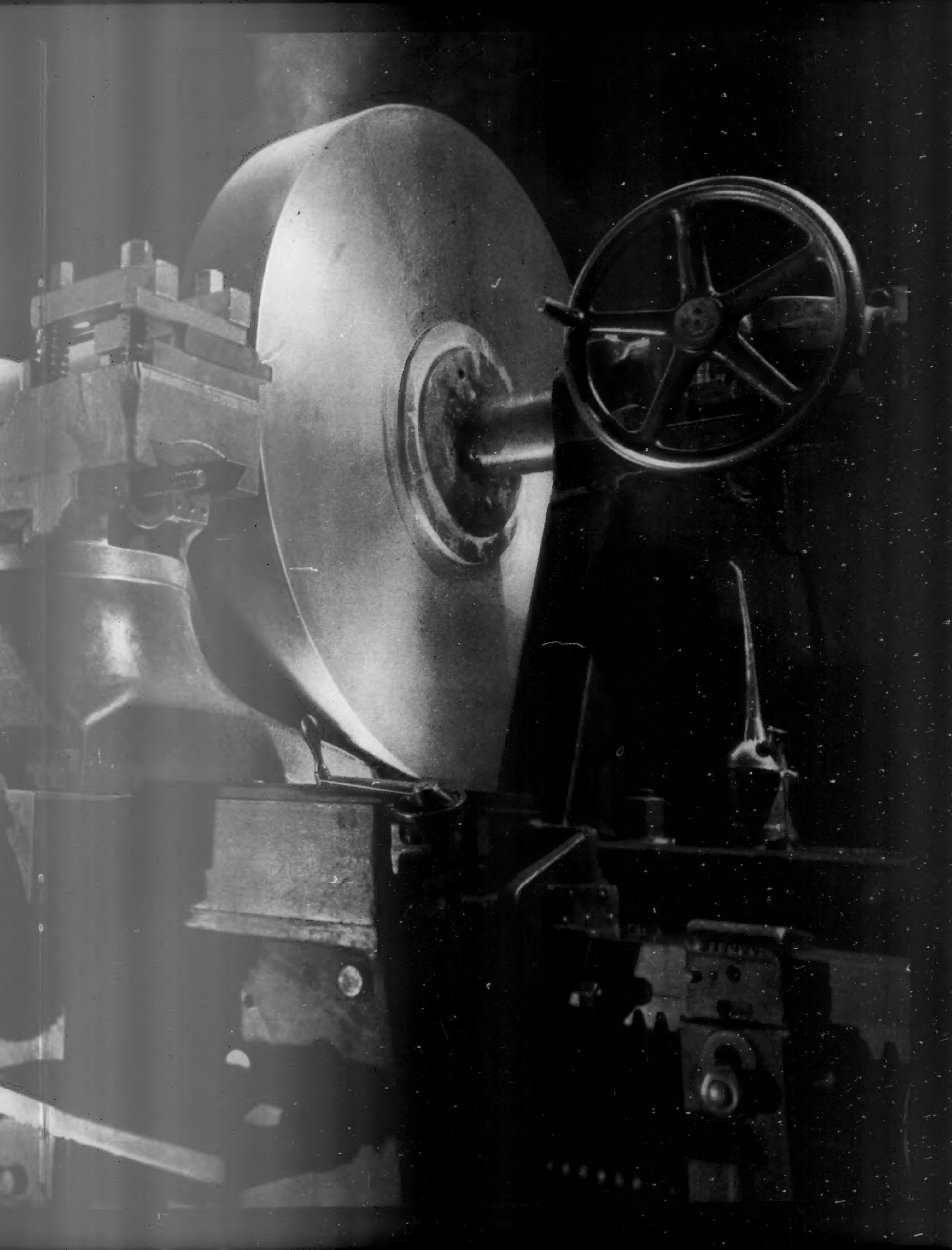
An adaptation of the standard fork and pin arrangement for side-mounted tap changers makes it possible to raise the tap changer assembly without removing the shaft extension through the compartment wall. An added feature of this design consists of a dial indicator on the tap changer shaft extension. This permits checking the actual tap changer position against the remote control indicator position.

The entire construction results in a minimum of time for inspection and replacement programs.

For further, more detailed information regarding these new products, write the Editors of ELECTRICAL REVIEW.

ON FOLLOWING PAGES: Machining the stub shaft for a waterwheel generator-hydraulic turbine unit for a southern dam.





HOW TO PARALLEL REGULATORS TO INCREASE FEEDER CAPACITY

Demands for additional power and higher continuity of service can often be met by operating step feeder voltage regulators in parallel. Here are five methods of keeping them in step.

W. L. Peterson and R. P. Marohn

TRANSFORMER DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

● Step type feeder voltage regulators are operated more and more in parallel as additional power and higher continuity of service are demanded of utilities. By installing regulators in parallel, capacity can be added to an existing feeder and continuity of service can be improved. Before regulators are operated in parallel, however, the requirements for parallel operation should be thoroughly understood so that proper provisions can be made in the regulator control circuits to prevent the paralleled regulators from running to opposite limits and staying there. Figs. 1 and 2 show standard three-phase feeder voltage regulators with ⅝% steps.

Before regulators can be paralleled, these conditions must be fulfilled:

1. The requirements for parallel operation of transformers must be met.
2. Provision must be made in the regulator control circuit to keep the load-ratio-control mechanisms close enough together so that the voltage difference will not cause objectionable circulating current.

Fig. 1 — Ready for shipment — 216 kva, 4160 volt, three-phase feeder voltage regulator with ⅝% steps, half-cycling operation.

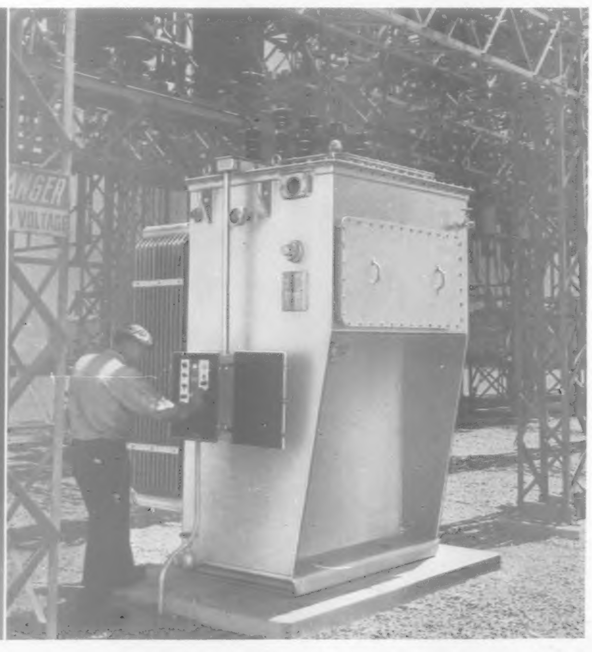


Fig. 2 — Regulators in parallel offer new capacity for overloaded lines. Shown is a standard unit in a western substation.

The first condition can be met by paralleling only regulators that have impedances nearly equal and voltage ratios such that, when the regulators are on the same tap position, the load current will be divided in proportion to the kva capacity of each regulator. Then circulating current will not be appreciable. It will be assumed that these conditions can be met.

The second condition can be met by using one of the five methods of keeping the regulators in step described in this article.

Why special control?

Power circuits to which parallel operation of regulators may be applied can be classified into three groups:

1. Those circuits in which the loop impedance is appreciable, allowing the regulators to be several steps apart without causing a voltage difference large enough to cause objectionable circulating current (Fig. 3a).

2. Those circuits in which the loop impedance is low and will allow the regulators to be no more than one step apart before the voltage difference will cause an objectionable circulating current (Fig. 3b).

3. Those circuits in which the loop impedance is negligible and will not allow the regulators to be even one step apart (Fig. 3c).

In considering a typical high-impedance loop (Fig. 3a), assume that the total impedance of the loop, including transformer and lines is 20%; that the high voltage feeder maintains a constant and equal voltage at all points; that the load has a lagging power factor and is equally divided between the paralleling lines when the regulators are on the same tap position. When the load on the output bus increases, regulators R_A and R_B are called upon to increase the voltage to compensate for the voltage drop to the load center, thereby maintaining constant voltage at the load center. One regulator will respond before the other since it is unusual for two independent mechanisms to operate simultaneously.

Assume that regulator A is the first to make a tap change. After regulator A raises its voltage, a differential voltage exists between the paralleling lines, and a circulating current I_0 flows from regulator A around the loop. Since the impedance of the loop is mostly reactive, the circulating current I_0 is very nearly at zero power factor.

How the currents flow in the regulator control circuits is shown in Fig. 4a, and the approximate vector diagram in Fig. 4b. The actual control circuits represented in Fig. 4a are shown in detail in Figs. 5 to 7. In regulator A, the circulating current is approximately zero power factor lagging; and, since the load current is also lagging, the resultant current is greater than the load current. In regulator B, the circulating current is approximately zero power factor leading, and the load current is lagging; hence the resultant current is less than the load current. Since the line drop compensator of the control circuit responds to the resultant current, the compensators will call for a raise in voltage in regulator A and a decrease in voltage in regulator B. As soon as the regulators respond, the larger voltage differential increases the circulating current, which in turn causes regulator A to run to the maximum raise position and regulator B to the maximum lower position.

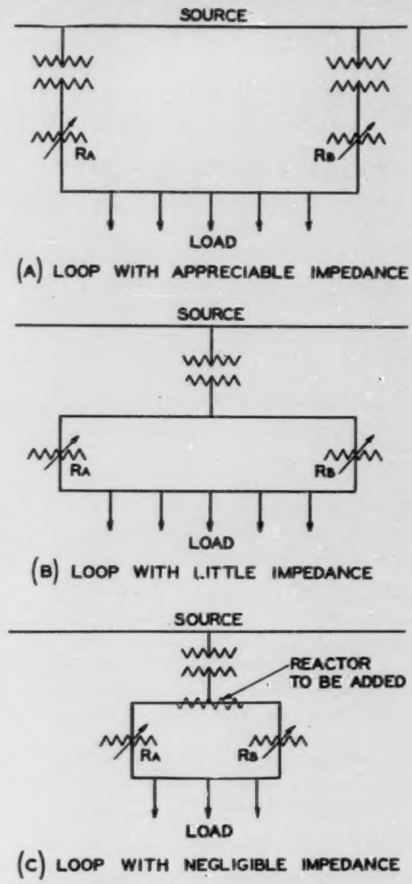


Fig. 3—Typical power circuits.

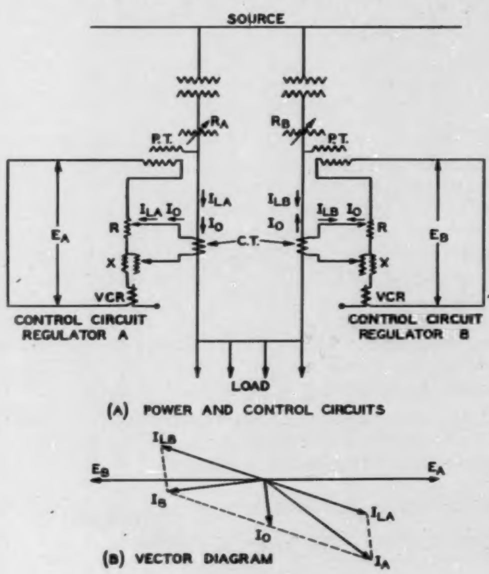


Fig. 4—Circuit diagrams.

Fig. 5—Feeder voltage regulator control panel.

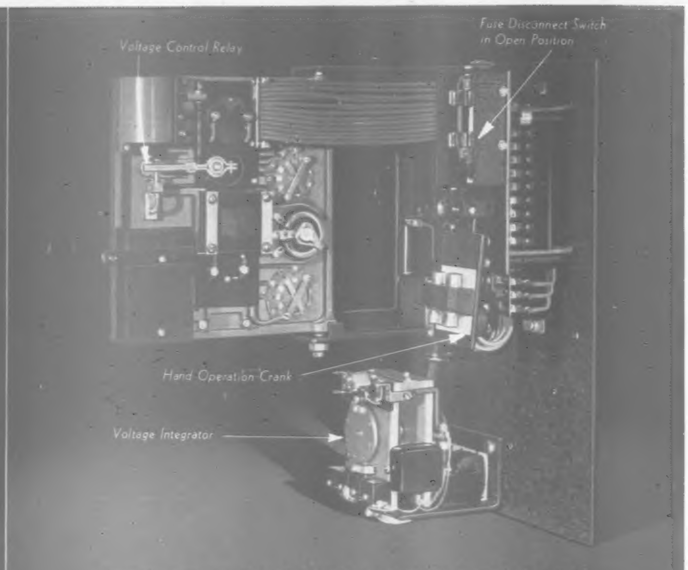


Fig. 6—Wiring of feeder voltage regulator control panel.

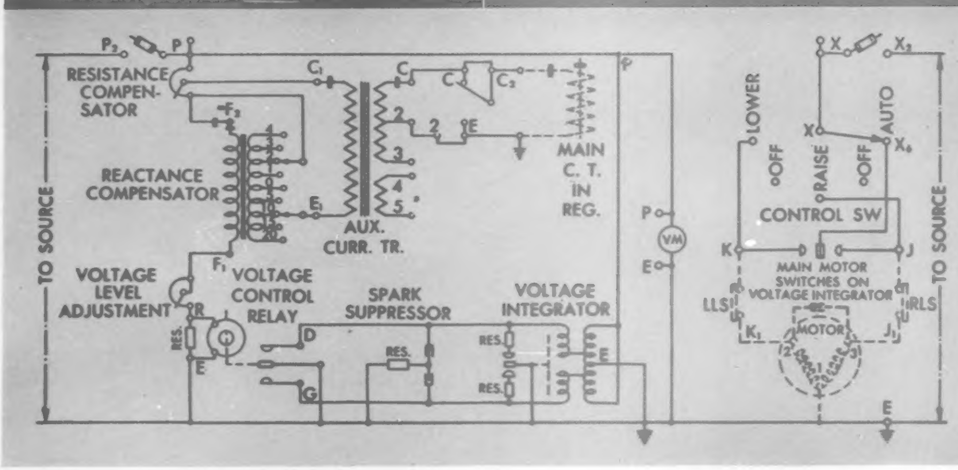


Fig. 7—Schematic control diagram for ⅝% step feeder voltage regulator

This large differential voltage causes the maximum amount of circulating current to flow. If the regulators have a standard range of $\pm$ 10% regulation, the differential voltage will be 20%, which will cause a circulating current of 100%. (Circulating current $=$ E% $\div$ Z% x 100 $=$ 20 $\div$ 20 x 100 $=$ 100%.) A circulating current equal to the full load current is of course objectionable. Therefore, special provisions must be made in the control circuits of the regulator to keep the mechanisms in step and thus limit the circulating current.

From this example, it is obvious that difficulties can be encountered when special provisions are not made for parallel operation of regulators.

Regulators on low-impedance loops

Of the circuits shown in Fig. 3, circuit A has a high impedance because the transformers add considerably to the loop impedance. Circuit B has low impedance because the only impedance in the loop is that of the regulators and the line. The maximum internal impedance of a regulator on the maximum raise or lower position may be as low at 0.5%, and it is seldom more than 1.0% (based on the line voltage with rated current flowing through the regulator). When the regulator is near the neutral position, the internal impedance of the regulator is further reduced until it may be almost zero and rarely more than 0.5%.

Regulators, therefore, add very little to the loop impedance. If the loop is short, as on a radial system such as Fig. 3c, the line impedance may be practically negligible, and circulating current would be excessive if the regulators were even one step apart. Since it is impossible to make the mechanisms operate at exactly the same instant, it is best to add enough impedance into the loop to allow the mechanisms to be one step apart.

Regulators on high-impedance loops

There are three reliable ways of modifying regulator

controls to permit paralleling in a high-impedance loop:

1. Negative reactance.
2. Cross-current compensation.
3. Paralleling reactor.

Regulators in a low-impedance loop can be paralleled by either direct drive or the lock-in method.

Negative reactance compensation

Negative reactance compensation in the voltage control circuit provides a means of keeping the regulators near the same tap position. Fig. 8 shows the reactive element of the line drop compensator reversed in the voltage control circuit. The effect on the voltage control relay is the reverse of the positive compensation obtained with the reactive element connected normally. If the source voltage decreases, both voltage control circuits of the regulators operating in parallel call for an increase in voltage.

If regulator A completes its tap change first, the increased resultant current I_A from the current transformer of regulator A will induce a voltage in the reactive element of the line drop compensator. Since the reactive element has been reversed, this voltage adds to the voltage across the contact making voltmeter and tends to make it balance. After regulator A has completed its tap change, the decreased resultant current I_B in the current transformer of regulator B will induce a voltage in the reactive element of the line drop compensator. This induced voltage will not be as effective as in regulator A because of the reduced resultant current, but the low voltage will cause regulator B to take a step in the raise direction.

At the instant regulator B completes its tap change, the circulating current is reduced, and the voltage is increased by the amount of one step. If one tap change is sufficient to balance again the voltage control relays, the regulators will remain on their respective tap positions which may be as many as three steps apart. The difference in tap position depends upon several conditions: the sensitivity and the setting of the primary relays, the proportionate share of the load taken by each regulator and the power factor of the connected load.

The advantage of this negative reactance scheme of parallel operation is that no special devices are involved in the voltage control circuit and no cross connections need be made between the two units. It is, therefore, very satisfactory for regulators in a loop placed at different stations. The disadvantage of this scheme is that the reactive element of the line drop compensator is used as a balance coil instead of a compensator for reactive voltage drop between the regulator and load center. If the power factor of the connected load is high, the resistance element of the line drop compensator can be used over-compensated, i.e., at a higher setting. If the power factor of the load is low or variable, the resistance method of over-compensation may not be satisfactory.

Cross current compensation

Cross current compensation is another way to keep the regulators near the same tap position. In this system the current transformer in the circuit of regulator A is connected to the line drop compensator of regulator B, and the current transformer of regulator B is connected to the line drop compensator of regulator A. Fig. 9 shows these connections; the reactive elements are not reversed, and the circuit has positive compensation for line voltage drop between the regulator and load center.

When the regulators are called upon to raise their output voltage and regulator A completes its tap change first, the resultant current I_B will be less than I_A because of the circulating current. Since the current transformer of regulator B is connected to the line drop compensator in the control circuit of regulator A, the voltage control relay of regulator A may balance at the first tap change, thus holding the regulator on that tap position. Because of the increased current I_A and the connections to the line drop compensator in the control circuit of regulator B, regulator B will complete its tap change and again be in step with regulator A. If no further increase in voltage is called for, the voltage control relays will again be balanced, and the regulators will remain in their positions.

The advantage of this method over that of the negative reactance method is that the reactive elements of the line drop compensators are effective in compensating for line drop rather than serving merely as balance coils, as in negative reactance compensation. The disadvantages of this method lie in that the regulators

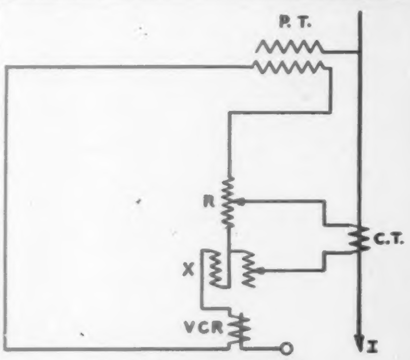


Fig. 8—Control circuit with negative reactance.

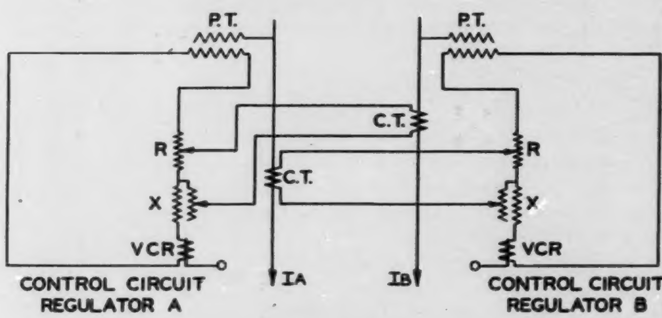


Fig. 9—Control circuits with cross-current compensation.

must be close enough to each other to make the wiring interconnections; and in the event one regulator is removed from service, the remaining unit is without compensation. This may be undesirable in some loops or radial feeders.

Cross connected reactor method

In this method two small, three-winding reactors are employed which are connected into the voltage control circuit of each regulator. One winding is in series with the line drop compensator and voltage control relay; the second winding in series with the current transformer which is connected across the line drop compensator; and the third winding is in series with the same coil of the other paralleling reactor. Fig. 10 shows this circuit and the necessary interlocking auxiliary switches which are open during parallel operation.

Closing the short-circuiting switch across the third winding of the reactor will make each voltage control circuit independent of the other in case it is desired to operate one of the regulators separately. The auxiliary switches on the breakers in the power circuit perform the same function, for they close automatically when a regulator is taken out of service or the bus tie switch is opened.

Windings No. 2 and No. 3 of the paralleling reactors have equal ampere turns. Under balanced load conditions, the resultant core flux in the reactor is practically zero since the current in winding No. 2 opposes an equivalent current in No. 3; hence no voltage is induced in winding No. 1, which is in series with the voltage control relay.

When the regulators are called upon to increase their output voltage and regulator A completes its tap change ahead of regulator B, the current in coil 2a will be larger than in 2b. This causes a current to flow in coils 3a and 3b, which are in series. The equivalent currents will then be suppressed in these coils, and a current will flow from coil 2a, causing a voltage to be induced in coil 1a which adds to the voltage of the voltage control relay of regulator A. The beam of the relay will raise, and the regulator will be stopped from further increasing its output voltage. The current caused to flow in coil 3b will induce a voltage in coil 1b which subtracts from the voltage of the voltage control relay of regulator B, thus causing the regulator to make its tap change and again be in step with regulator A.

This method has the same advantages as cross current compensation; and in addition, if one unit is removed from the circuit, reactance compensation on the remaining regulator is still obtained. The disadvantage in comparison with the cross current compensation method is that two specially designed reactors are required. However, the reactors are small and can be installed in the control cabinets of the regulators.

Direct drive

In the direct drive method, the tap changing switches of the regulators to be operated in parallel are coupled together and driven by one motor and mechanism. Usually the regulators are in separate tanks, and the tap-changing panels are connected by a shaft running between the two units. One driving motor is used which can be installed at either regulator or midway between the two units, and only one voltage control circuit is necessary.

When the voltage control circuit calls for a tap change, the driving mechanism actuates both tap changer panels to make a tap change. However, both tap changer panels do not remain exactly in step because the moving contacts of one regulator may reach their stationary contacts a fraction of a second before the other unit completes its tap change. Therefore, during the transition period the regulators operate one step apart. Enough loop impedance must be provided to limit the circulating current during the small interval that one unit may lag behind.

The advantage of this scheme lies in the use of one driving mechanism and one voltage control circuit and the positive mechanical interlock. The disadvantages are the necessity of very accurate alignment of the two units, troublesome stuffing boxes, supports for the shaft between the two units, and, if one unit is removed from service, the other unit will also be put out of operation.

Electrical interlock method

The electrical interlock method provides a circuit which keeps two regulators electrically interlocked with auxiliary relays, and the regulators remain within one step of each other. The auxiliary circuit has two relays, two switches actuated by means of cams on the tap changing mechanisms of the regulators, a two-position master transfer switch, two manual control switches, and two potential transformers, each of which is connected across the series winding of a regulator. Only one automatic voltage control circuit is needed.

Figure 11 shows a schematic diagram of the electrical interlock in the motor circuits for the two regulators. No special connections are made in the voltage control panel. The circuit is such that the regulators can be only one step apart. If several tap changes are necesary to correct the voltage, one regulator will operate and then wait for the other. After

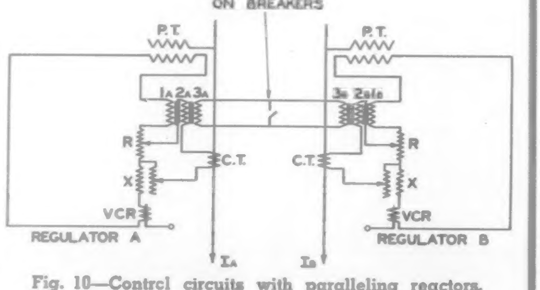


Fig. 10—Control circuits with paralleling reactors.

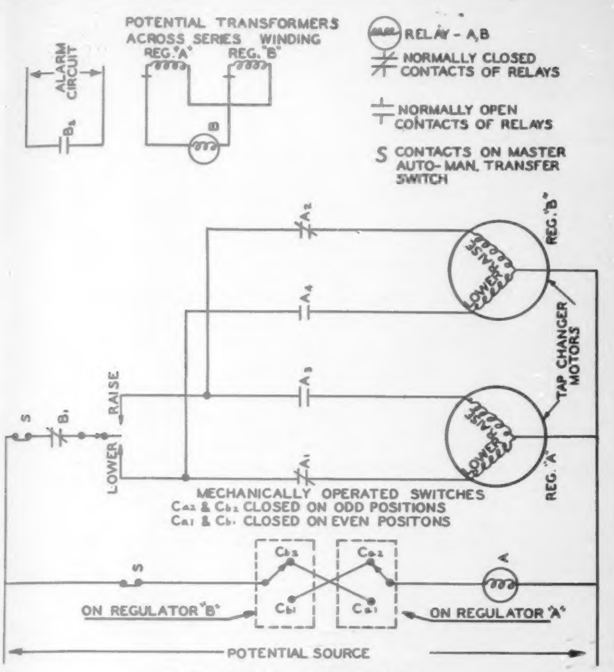


Fig. 11—Interlock method.

the regulator that was lagging behind catches up, the leading regulator takes another step toward correcting the voltage. This is accomplished by the action of relay A and the mechanically operated switches. In the appendix is a step-by-step description of the operation.

The advantage of this method of parallel operation is that the regulators are locked-in to operate not more than one step apart, and only one voltage control panel is necessary. The disadvantage is that relays and switches and interconnecting wiring between the two units are required. However, electrical interlocking is very practical when the regulators are installed at the same station.

The circuit described is one of the simplest for providing an electrical interlock between units. There are several variations of this fundamental circuit in common use.

Summary

To operate regulators in parallel, it is necessary that the requirements for parallel operation of transformers be met by the paralleled circuit. In addition, control means must be provided to keep the regulators close enough together in position so that the circulating current will not exceed a safe value. This may require an increase in the impedance of the paralleled circuits. In practice, the means selected for keeping the regulators in step is determined by the proximity of the regulators and the type of circuit in which they operate.

Appendix

The operation of the electrical interlock circuit is as follows: Fig. 11 shows the position of the mechanical switches and contactors when the two regulators are on the same tap position and the master transfer switch in the automatic position. When a raise in voltage is called for by the voltage control relay, the raise switch on the voltage integrator relay is closed, completing the circuit to the motor on regulator B; and the circuit to the motor on regulator A is still open at contactor A_3. Regulator B will complete its tap change.

At the instant this tap change is made, the cam-operated switch on regulator B will open the circuit through Cb_2 and close Cb_1, thus completing the circuit through relay A, which will open contactor A_2 and close contactor A_3, completing the circuit to the motor on regulator A.

When regulator A has completed its tap change, the cam-operated switch on regulator A will open at Ca_2 and close Ca_1. The circuit through relay A will be opened, and contactors A_2 and A_3 will drop to their original positions. The regulators are now set for the next tap change, and this cycle will repeat until the voltage control relay is balanced.

It is, however, possible that the voltage control relay may balance before the trailing regulator makes its tap change, allowing the regulators to operate one step apart. This is not objectionable if the loop in the power circuit has enough impedance to limit the circulating current between the two units.

The sequence of operation for lowering the output voltage is the same as described. Under these conditions, regulator A makes its tap change first with regulator B trailing.

The output voltage of both regulators can be manually controlled by switching a transfer switch on the voltage control panel to either raise or lower position, and the sequence of operation will be the same as under automatic control. With the master transfer switch in the manual position, either regulator can be manually controlled by means of manual control switches.

If for any reason the regulators should get more than one position out of step, relay B, connected into the potential circuit across the series windings of the two regulators, provides protection. This relay detects the difference in voltage between the two regulators, and the design of the relay is such that it will pick up when the regulators are two steps apart. When the relay picks up, contactor B_1 opens, cutting off power to both operating motors. The leading regulator will then be stopped from further advancing, and the regulators will remain two steps apart and will be locked in this position until they are brought into step again by means of a master transfer switch and manual control switches.

When relay B picks up, contactor B_2 closes. This contactor can be used to close an alarm or light circuit to inform the operator that the two regulators are more than one step apart.

ARE YOU GETTING FULL PATENT PROTECTION?

A single idea often leads to several inventions — devices, machines, methods, and designs. All may be patentable.

D. Journeaux

PATENT ATTORNEY • ALLIS-CHALMERS MANUFACTURING COMPANY

● In spite of centuries of exposure to the challenge of inquisitive minds, the old adage "Necessity is the mother of invention" seems never to have been seriously questioned. Who indeed, upon seeing a need for improvement, has not exclaimed: "Somebody ought to invent something to take care of that!" Then, if the problem was proposed by someone with an inventive mind, he immediately added: "Let me see what I can do about it."

This little soliloquy, spoken or merely thought, has probably been the champagne that launched many of the inventions now making us successful in war and in peace. An inventor usually aims to provide some means or device for accomplishing a useful result, whether or not a need exists at the moment.

Mere ideas not patentable

The desired result may be new, but the mere conception of a new result does not constitute invention, according to the standards of the United States Patent Office, and such a conception is not enough to warrant a patent in this country. Patents are granted for a means for accomplishing a desired result on condition that such means be new and constitute invention.

The means may be altogether new, or a new combination of old means. It may serve to produce a new result, or it may merely produce an old result in an improved manner.

But the inventor who has applied for a patent for his new device very often has not exhausted the protection available to him under the patent laws. For example, he may be able to patent the method of operation or the device. On the other hand, this method may be old and, therefore, obviously unpatentable; or it may be new, but no more than merely the inherent operation of the device. In the latter case, it is considered that the device and its operation constitute a single invention and therefore are not separately patentable.

Device and method of operation patentable

If the method of operation is new and performed manually or by devices other than the one sought to be patented, the device and its method of operation may be separately patentable. This is true whether or not they occurred simultaneously to the inventor. Whether the device and the method should be claimed in separate patents or in different claims of a single patent is merely a question of procedure. If separate patents are to be obtained, however, the application for the second to issue should be made before the first one issues.

The drawings of a famous pair of patents, now expired, that were granted for what might be assumed to be a single invention are shown in Fig. 1. Patent 555,190 claimed what would now be called a split-phase motor, in which the main stator circuit, connected to an a-c source, energizes an auxiliary stator circuit by induction. Patent 511,915 claimed the method of operation of the motor by inducing current in one stator circuit from the other. A court held that the two patents were for different inventions, on the ground that it was probable that the patented process could be utilized in devices which are not the mechanical equivalent of the patented motor. Having made two separate inventions, the inventor was entitled to patents securing both of them against infringement.

Device and machine for making it

After inventing a new device, the inventor should give some thought, as he too frequently fails to do, to the possibility of making it. In this connection he may also invent new manufacturing processes and new machinery for performing the processes. Of course,

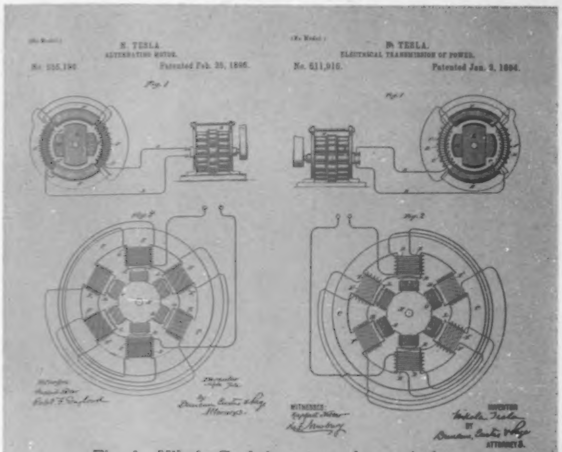


Fig. 1—Nikola Tesla's patents for an induction motor and its method of operation.

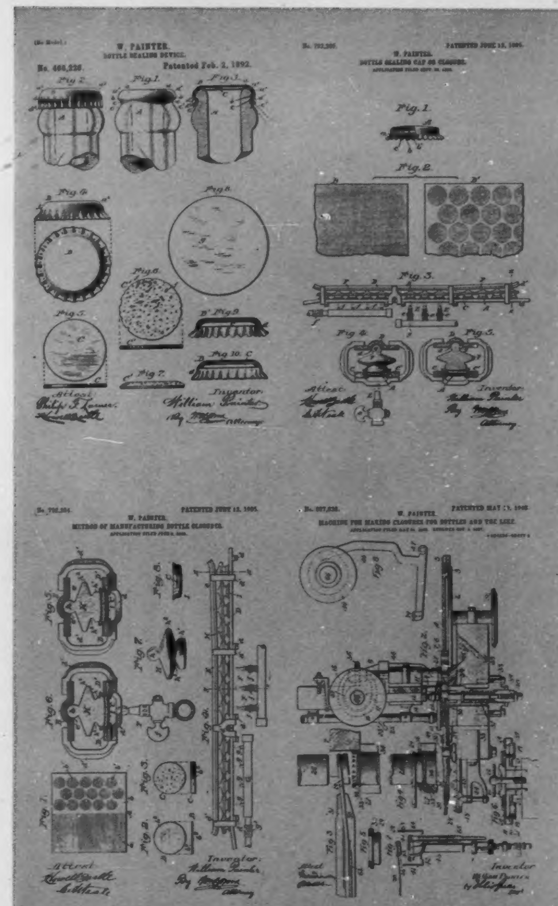


Fig. 2—William Painter's patents for a bottle cap, an improved form of the cap, a method of securing the gasket in the cap, and a machine for applying the gasket.

the inventor's mind need not necessarily follow that particular sequence of thought. When a device is merely an improvement of an old device, it may be hard to determine whether a new machine was developed for making the improved device, or whether the improved device was the natural result of the improved machine.

From the viewpoint of patentability, a machine and its product are entirely separate, and each may be patented if it is new. The process performed by the machine, which is its method of operation, may however be patented only if it is new and if it can be performed by other machines or manually.

The four patent drawings in Fig. 2 illustrate the point. This invention is the ubiquitous bottle cap. Patent 468,226 is for the bottle cap as developed by its inventor to about the form in which we find it today. Patent 792,285 is for an improvement in the composition of the sealing gasket in the cap. Patent 792,284 is for a method of securing the sealing gasket to either form of cap, and patent 887,838 covers the machinery for performing that method.

These four patents have withstood successfully the test of trial in court. The single idea of the bottle cap led its inventor and others to make numerous other patentable inventions relating to the form of the cap and to the machinery for making the cap, applying it to a bottle and, last but not least, removing it from the bottle.

Mechanical and design patents

The patents so far discussed are all of the general type known as mechanical patents, which are granted only for purportedly utilitarian inventions. Inventions of a purely ornamental nature, or design, are presumably without utility and are therefore excluded. However, it would be jumping to conclusions to assume that the Patent Office looks on ornamentation

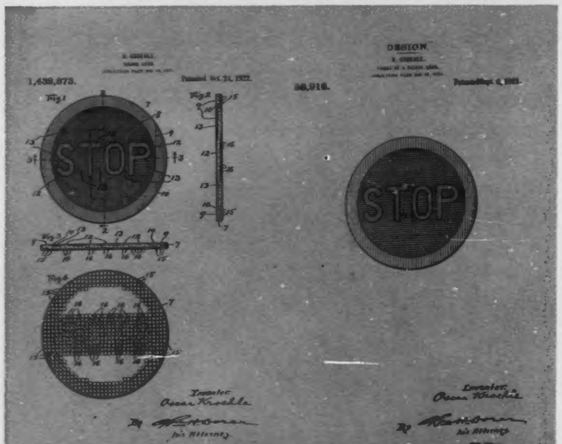


Fig. 3—Oscar Kroehle's patents for automobile signal lens of improved optical properties and for a design of lens.

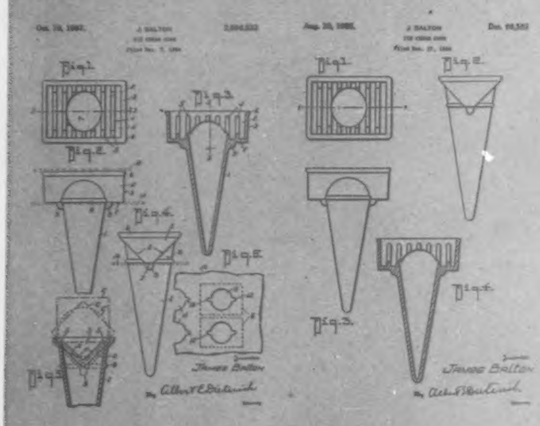


Fig. 4 (above)—James Balton's patents for a gripping ice cream cone and for a design of the cone.

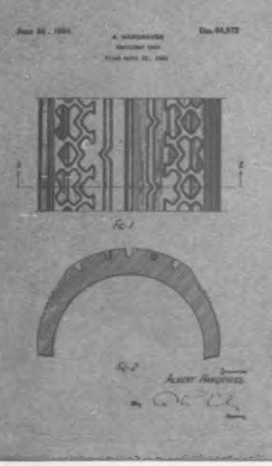


Fig. 5 (at left)—Albert Hargraves' patent for a design of automobile tire tread. Corresponding mechanical patent was refused.

with contempt. On the contrary, patents of another type, called design patents, are granted for new, original and ornamental designs.

A device invented for a useful purpose and subject to protection by mechanical patent may also have ornamental value. It is also true, although perhaps less evident, that an ornamental object of which the design is patentable may also involve some new and useful function. The result is that a mechanical patent may be granted for the useful feature of a device, and a design patent may be granted for the ornamental feature of the same device. The two patents, since they are of different kinds, are not required to be co-pending in the Patent Office. If the first of the two patents to issue discloses both the useful and the ornamental features, then application for the other must be made within one year after issuance of the first.

Ornamental and useful features patentable

The ornamental and the useful features of a device may or may not have occurred to its inventor simultaneously. Both may be patentable, but only if they are clearly distinguishable from each other.

For example, the automobile signal lens shown in Fig. 3 has a useful feature residing in the provision of opaque portions and translucent portions having particular optical properties. Its ornamental feature lies in the arrangement of the lettering and border. Only the useful feature is claimed in the mechanical patent, and only the ornamental feature is claimed in the design patent. Although both are provided in a single lens, the two features have nothing in common, and they could be used separately in different lenses.

Likewise, the ice cream cone shown in Fig. 4 has a new ornamental configuration and also a novel useful feature in the transverse ribs for gripping the block of ice cream. The ornamental design of the cone is claimed in the design patent, and the arrangement of the ribs within the cone is claimed in the mechanical patent.

When the mechanical feature and the design feature of an object are indistinguishable, the grant of both a mechanical patent and a design patent would amount to granting two patents for the same thing. For this reason, a mechanical patent for an automobile tire characterized by two continuous circumferential ribs was refused to the inventor, who already had a

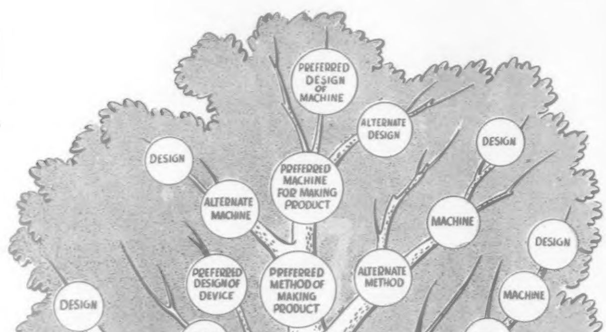


Fig. 6 — Family tree of related inventions.

design patent, shown in Fig. 5, directed to the same feature.

Family tree of related patents

As evidenced by these examples, the pursuit of a single idea in achieving a result may lead an aggressive inventor to develop a related group of patentable inventions. In general, these inventions will fall into the following classes:

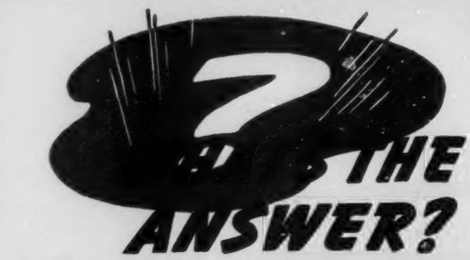
1. Methods of obtaining the desired result.
2. Devices for obtaining the desired result.
3. Methods of making the devices.
4. Machines for making the devices.
5. Designs of the devices and of the machines.

Sometimes each class will contain a single idea, but more often the inventor will devise alternate devices, methods, machines, and designs. Indeed, one of the problems facing inventors is to choose, among alternates, the invention on which to concentrate. Promising alternate inventions may be retained to fall back on in case of disappointment in the results of the preferred invention, and these alternates should be patented if possible so that they will be available when needed. Those that do not appear promising naturally drop out of sight as dead branches fall from a tree.

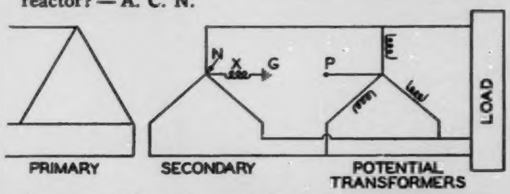
Related inventions, like human beings, have family trees, but their patterns need not have the uniformity resulting from genealogical silviculture. The inventor starts from a desired result as the ground in which the tree is to grow. The resulting growth may be a single device, sometimes preceded by the method of obtaining the desired result. If the device is further looked upon as being the product of a machine, the tree may sprout a method of making the device and the machine for making the device by that method. Finally, ornamental designs for the device and the machine may provide ornamental even though somewhat unbotanical foliage.

As sketched in Fig. 6, the tree may have more than one trunk, and each trunk may have many branches when variations are provided for the different preferred inventions. Successive improvements of the different inventions may increase the number of branches indefinitely. To carry the comparison further, the tree will often carry the seeds from which a motley array of mighty giants and scrubby dwarfs will later grow.

The growth of the invention tree often progresses regularly from the root to the crown, but it is quite possible to make it start from the top or even from the middle. This may be an irrational way to grow a tree, but after all this is an age of wonders!



Question—We have a 30,000 kva wye-connected transformer bank with a one ohm reactor in the neutral to limit fault currents, as shown in the sketch. Four-wire metering with standard connections is desired, but during short circuits a 3800 volt drop may occur across the reactor, making the neutral connections to the potential transformers dangerously high above ground. Can the neutral of the potential transformers be connected to the grounded side of the reactor?—A. C. N.



Answer—When the neutral of the potential transformer is connected to point P in the sketch, the energy and demand metered will be that supplied to the load. On the other hand, if the neutral of the potential transformer is connected to point N, the energy metered would include losses in the reactor.

Actually the losses and kva demand of the reactor would be very small. Fortunately, in this case the correct connection is the one desired from the standpoint of keeping the potential transformers at ground voltage.

Question—A 1200 ampere, 15 kv circuit breaker mounted in a cubicle is running hot. Normal current is 1000 amperes although the breaker sometimes carries a 25 to 30 percent overload. What can we do to make the breaker run cool?—A. P.

Answer—Breaker contacts in oil can have a temperature rise of 30 C in a 40 C ambient according to AIEE standards. Higher temperatures for tank tops are permitted. Thus, a breaker that is too hot to touch may not necessarily be overheated.

Too small buses, poor bus joints, overloading, restricted ventilation, and poor contact from maladjusted linkages, or damaged or oxidized contact surfaces can contribute to breaker overheating. If the ambient temperature exceeds 40 C, it may be necessary to improve air circulation. It is easy to check adjacent bus joints to see that they are not running hotter than the breaker.

High-resistance copper oxide tends to form on breaker contacts, causing higher temperatures and increased rate of forming of copper oxide. This oxide can be cleaned off with fine emery cloth, backed with a hardwood block. Most modern breakers have contacts plated with silver, which forms a low-resistance oxide, preventing the pyramiding of heating effect. Silver plating one or both of the cleaned contact surfaces will reduce the frequency of maintenance.

Deformed or annealed brushes should be replaced and so adjusted that the contact area and pressure are adequate. Excess carbon or acid in the oil will also cause heating, and unsatisfactory oil should be replaced with new oil.

"What's the Answer?" is conducted for the benefit of readers of ELECTRICAL REVIEW who have questions on central station, industrial or power plant equipment. Send all questions to the Editors of ELECTRICAL REVIEW.

DESIGNING SPECIAL SLIDE RULES

Quick and accurate solutions to routine equations with easy-to-make special slide rules relieve the engineer of "strong arm" work, allow him to concentrate on more important problems. Here's how to make them.

R. C. Odell

TRANSFORMER DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

● A slide rule is a mechanical means of solving mathematical equations. Since its invention shortly after the year 1620, the slide rule had been used only by the engineering profession until recently when it filtered into other occupations. The "slip stick" has proven an invaluable aid in speeding calculations, and its accuracy for most work is more than satisfactory.

Increased production in shops during the last two decades has made it necessary for engineering departments to decrease the time spent for slide rule calculations wherever possible. There are many equations, long and tedious to solve even by the conventional slide rule, that can be represented on a special slide rule. Then by a simple setting of slides, and perhaps an addition, the solution may be had quickly and with reasonable accuracy.

The special slide rule is not merely an engineering tool; it may be used with equal effectiveness in any field where numerous approximate calculations are made with the same formula. For example, in photography a special slide rule is used to determine the size of lens opening; and in chemistry a rule is used to provide quick solutions to special problems.

With a special slide rule the likelihood of errors is reduced, mental effort is minimized, time required for a solution is shortened, and sometimes greater accuracy can be obtained.

Definitions

Before the design of special slide rules is explained, two terms will be defined.

1. A "scale" is a straight line upon which are marked cross lines to correspond with a set of numbers arranged in the order of their magnitude. The function of a variable, v, may be represented on a scale if each value of the variable determines the single value of some function of that variable, f(v). If successive divisions are in equal steps, the scale is uniform; if they are not, the scale is non-uniform.

2. The "scale modulus," m, is the ratio of the length of the scale to the range of the function of the variable represented in that distance. Then if "x" represents any linear distance along a scale from an origin, $x = mf(v)$ by definition. This equation is known as the equation of the scale.

In the appendix the following condition is established for determining when an equation may be set up on a slide rule:

Whenever the relation among several variables is such that it may be reduced to the form: — "the sum of several terms, each containing only one variable, equals a constant" — a slide rule can be constructed which will represent the relation between the variables, and which will enable the value of a missing variable to be determined if the remaining ones are known.

A four-variable slide rule

The equations must first be put into the general form in accordance with the above rule.

$$A - B + C - D = O$$

where A is a function of a
B is a function of b
C is a function of c
D is a function of d.

It is immaterial in what order the scales are placed on the rule, but for consistency in design some standard should be followed. Therefore, place A on the lower stationary scale, and D on the upper stationary scale. B may be placed on the lower part of the sliding scale and C on the top part of the sliding scale. Such a slide rule is used by setting it so that two of the known quantities are opposite each other; then the unknown quantity may be read opposite the value of the third known quantity. For example, if A, B, and C are known, values of A and B can be set opposite each other, and the value of D read opposite C.

AT LEFT: Under pressure of 50 tons, the commutator for a 1500 hp d-c motor is tightened in a press. Following this, it will pass through four cycles of stationary seasoning, one of rotary seasoning.

After fixing the order of the scales, the next step is to determine the range of each function and plot the values A, B, C, and D with reference to some plotting scale — marking the divisions with corresponding values of A, B, C, and D. The scales may then be located on the rule by solving an example.

Constructing a slide rule

The following detailed rules may be followed in making a slide rule for four variables.

1. The equation to be used is written in its original form.

2. The equation is arranged in proper form so that a slide rule can be applied to it; i.e., in the form of addition or subtraction of the variables. (If the equation is too difficult to put into this form even by writing it in logarithmic form, it may be possible to introduce auxiliary variables and break up the one equation into separate equations, each of which may be solved by special rules.)

3. The terms of the equation are arranged in the order that they are to be placed on the rule, with D the quantity to be solved for last.

4. The values for the variable are chosen. The variable A will have values between the limits of A_1 and A_2, B between B_1 and B_2, C between C_1 and C_2, and D between D_1 and D_2. The scale modulus must be such that the length of the longest scale will not exceed the length of the slide rule blank. If A has the longest scale and $A_1 = 4$, $A_2 = 29$, then the range will be $A_2 - A_1 = 29 - 4 = 25$. For a scale length of ten inches on a twelve-inch blank, the scale modulus, m, must be $10 \div 25$ or 0.4.

5. With the scale modulus determined, the equations of the scales may be written:

$$A = ma$$
$$B = mb$$
$$C = mc$$
$$D = md$$

6. Each scale may then be plotted on a strip of heavy paper.

7. It is usually best to place the right hand limits of the two longest scales together regardless of their position on the rule — i.e., whether a sliding or a fixed scale — otherwise an abnormal length of rule may be necessary. Then by solving an example (the answer being known, of course), the third and fourth scales may be roughly located. After this is done, the third scale can be glued in place. Finally, the fourth scale is accurately located by solving the example again and glued on the rule.

8. Next, check the scale layout and the index location by solving several examples. The last step is to label all the scales properly.

Example

A special slide rule to solve the common emf equation of a transformer will be developed by following the rules, step by step.

1. $$B = \frac{34.9 \times 10^5 \times E}{f\,A\,N}$$

where B = flux density in gausses
E = voltage across transformer winding
f = frequency in cycles per second
A = cross section area of core in square inches
N = number of turns on core

2. This equation has five variables in it, but it may be simplified by lumping together two of them into one variable, leaving an equation of four variables which may be solved with a slide rule of two fixed and two sliding scales:

Let $\frac{E}{N} = V_t$ or volts per turn.

then $$B = \frac{34.9 \times 10^5\, V_t}{f\,A}$$

From inspection of the equation and applications of logarithms, the equation may be rewritten:

$$\log A + \log f - \log V_t + \log B = \log (34.9 \times 10^5)$$

or

$$\log A + \log f - \log V_t + \log B = 6.54283.$$

3. Then when the terms are rearranged for placing on the slide rule, the above equation becomes:

$$\log B - \log V_t + \log f + \log A = 6.54283.$$

The equation for f(B) is placed on the lower stationary scale, that for $f(V_t)$ on the lower sliding scale, for f(f) on the upper sliding scale, and for the part to be solved for f(A) on the upper stationary scale.

4 and 5. These rules are incorporated in the table shown in Fig. 1.

Variable	Limits of Variable	f (Variable)	Range of function	m	Equation of Scale	Length of Scale, in.
B	5,000 to 18,000	log B	$\log\frac{18000}{5000} = .55630$	10	10 log B	5.563
V_t	1.5 to 15	log V_t	$\log\frac{15}{1.5} = 1.00000$	10	10 log V_t	10.00
f	25 to 180	log f	$\log\frac{180}{25} = .85733$	10	10 log f	8.5733
A	10 to 100	log A	$\log\frac{100}{10} = 1.00$	10	10 log A	10.0

Fig. 1

Note that the scale modulus chosen was 10. This greatly simplifies the calculations since, in plotting the scales, the logarithmic values of the functions may be easily multiplied by 10. Of course, in many types of equations, a smaller or larger modulus may be necessary. In this case the length of the longest scale is 10 in. which fits on a 12 in. blank easily; hence a modulus of 10 is the optimum value.

Inspection of the table, Fig. 2, shows how values of the variable may be found in order to plot the equation on a scale. A tabulation, such as shown in Fig. 2, is helpful in keeping values orderly for plotting. The numbers are carried out to only two places because further accuracy is lost in plotting the scales.

B	10 log B	V_t	10 log V_t	f	10 log f	A	10 log A
5,000	37.00	1.5	1.76	25	14.00	10	10.0
6,000	37.78	2.0	3.01	50	17.00	15	11.76
7,000	38.45	3.0	4.77	60	17.78	20	13.01
8,000	39.03	4.0	6.02	180	22.57	30	14.77
9,000	39.54	5.0	7.00			40	16.02
10,000	40.00	6.0	7.78			50	17.00
11,000	40.41	7.0	8.45			60	17.78
12,000	40.79	8.0	9.03			70	18.45
13,000	41.14	9.0	9.54			80	19.03
14,000	41.46	10.0	10.00			90	19.54
15,000	41.76	15.0	11.76			100	20.00
16,000	42.04						
17,000	42.30						
18,000	42.56						

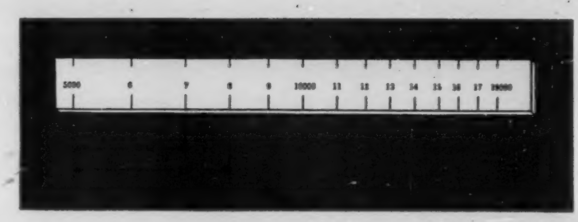
Fig. 2

6. Before the scales can be laid out and plotted, the direction of the scales must be determined. If the first term of the equation increases to the right, then the odd numbered terms increase to the right, i.e., one and three; and all the even numbered terms increase to the left, i.e., two and four; except where the term is preceded by a minus sign, in which case the direction is reversed. Then 10 log B increases to the right, 10 log V_t increases to the right (because of the minus sign), 10 log f increases to the right and 10 log A increases to the left. The scales may be plotted directly from Fig. 2. In the first column, the mark or designation for B = 5000 is 37.00 in. from some zero point, that for B = 6000 is 37.78 in. from the same zero point. The other scales, of course, are similar. But if desired, the table may be simplified by letting the origins be at B = 5000, V_t = 1.5, f = 25, and A = 10. A simplified table is shown in Fig. 3.

B	10 f_1(B)	V_t	10 f_1(V_t)	f	10 f_1(f)	A	10 f_1(A)
5,000	0.00	1.5	0.00	25	0.00	10	0.00
6,000	0.78	2.0	1.25	50	3.00	15	1.76
7,000	1.45	3.0	3.01	60	3.78	20	3.01
8,000	2.03	4.0	4.26	180	8.57	30	4.77
9,000	2.54	5.0	5.24			40	6.02
10,000	3.00	6.0	6.02			50	7.00
11,000	3.41	7.0	6.69			60	7.78
12,000	3.79	8.0	7.27			70	8.45
13,000	4.14	9.0	7.78			80	9.03
14,000	4.46	10.0	8.24			90	9.54
15,000	5.76	15.0	10.00			100	10.00
16,000	5.04						
17,000	5.30						
18,000	5.56						

Fig. 3

Scales may then be plotted from the tabulations in either Fig. 2 or Fig. 3 — remembering, of course, that the scale of A increases to the left. Fig. 4 shows how



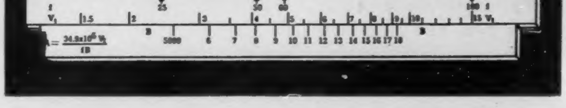
the scale for B is plotted. The others are plotted similarly.

7. It is now necessary to locate the scales (on a 12 in. blank rule) with respect to each other so that the equation may be correctly solved. The two longest scales are A and V_t — their origins are placed on the same vertical line. Since A is the unknown quantity, it is placed on the top stationary part of the slide in accordance with the general form of the equation. The scale for V_t is put on the lower sliding portion of the rule, as shown in Fig. 5.

The other two scales are located by trial. Place the f scale on the top of the slide so that f = 180 coincides with A = 10 on the upper stationary portion. To locate the B scale, an example may be solved. Let B = 10,000, V_t = 10, f = 60. Solving for A, after these values are substituted, gives 58.3. Thus, in order to locate the B scale, the slide rule is worked backwards — 60 on the f scale is set opposite 58.3 on the A scale. Opposite 10 on the V_t scale, 10,000 on the B scale is placed, and then the B scale is glued on the rule.

This choice of scale positions placed the B scale approximately at the center of the rule. If the choice had been such as to allow the B scale to fall off the rule, then another trial position for the f scale would have been necessary.

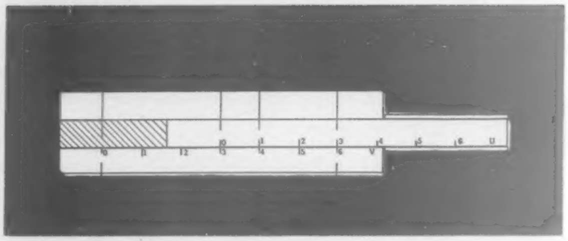
8. The last step is to check the scale layout by solving several examples, the answers of which are known. All scales are then properly marked so that the rule may be used without confusion by anyone not familiar with it. For reference the equation solved is written on the rule. The special slide rule used to illustrate the method is a simple one, but the same methods still guide the making of special rules for other equations.



APPENDIX

Elementary theory

All slide rules operate on a simple principle: the addition of scales, the lengths of which are propor-



tional to the value of the functions represented on the scales. As an example, a slide rule with two scales — one fixed and the other movable — is shown in Fig. 6. The stationary scale represents some function of the variable v, and the sliding scale some function of the variable u.

Referring back to the definitions, it may be seen that the equation of the stationary scale is then $x = mf(v)$, and that of the sliding scale is $y = mf(u)$. Choosing a reference line through o on the stationary scale and calling the distance between the origins of the two scales d makes it possible to write these expressions. The scale modulus m is chosen the same for both equations.

$$x_6 - y_3 = d$$
$$x_4 - y_1 = d$$

Since

$$x_6 = mf(v_6)$$
$$x_4 = mf(v_4)$$

and

$$y_3 = mf(u_3)$$
$$y_1 = mf(u_1)$$

Then

$$mf(v_6) - mf(u_3) = mf(v_4) - mf(u_1)$$

and

$$f(v_6) - f(u_3) = f(v_4) - f(u_1) \quad \dots\dots\dots\dots\dots \quad (1)$$

Equation (1) is the form of relation between the variables u and v that may be solved with one stationary scale and one sliding scale. The figure illustrates scales that are uniform, and the subscripts refer to division marks on the scale. If then, $f(u) = u$ and $f(v) = v$, we may substitute in the equation the subscripts and have

$$6 - 3 = 4 - 1$$
$$0 = 0$$

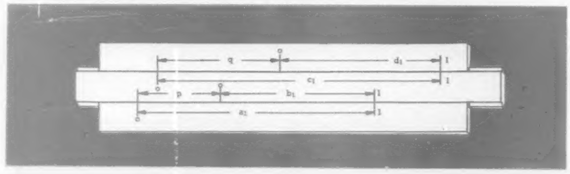
It is obvious then that a slide rule with uniform scales may be used for addition or subtraction and that this rule with two sliding scales solves the equation $A = u + v$.

Such a slide rule may also solve an equation in which $f(u) = \frac{1}{u}$ and $f(v) = \frac{1}{v}$, or $f(u) = \log u$ and $f(v) = \log v$, etc.

Slide rule for four variables

The type of equation relating four variables will be developed next. The equation for three variables is evolved by the same method used in obtaining that of four variables; and, since the four variable equation is the more difficult of the two, it will be developed. Four scales represent each of the four variables, two stationary and two sliding scales.

In Fig. 7 the lowest scale is for the variable u with the equation of the scale $a = mf(u)$. On the slide the equation of the bottom scale is $b = mf(v)$; the top scale $c = mf(x)$. The equation of the top stationary scale is $d = mf(y)$. Note that the scale modulus m is the same for all scales. The origin of each scale is designated at o.



The origin of the v scale is p in. to the right of the origin of the u scale, and the origin of the y scale is q in. to the right of the origin of the x scale. For any position such as 1, then

$$p = a_1 - b_1$$
$$q = c_1 - d_1$$

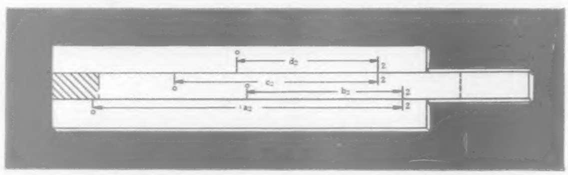
or

$$p = mf(u_1) - mf(v_1)$$
$$q = mf(x_1) - mf(y_1)$$

Now suppose the slide is moved r in. to the right as shown in Fig. 8, with 2 representing some new setting, then

$$q + d_2 = c_2 + r, \text{ or, } q - r = c_2 - d_2$$
$$a_2 = p + b_2 + r, \text{ or, } p + r = a_2 - b_2$$

and



$$q - r = mf(x_2) - mf(y_2)$$
$$p + r = mf(u_2) - mf(v_2)$$

If these last two equations are added, r is eliminated:

$$p + q = mf(u_2) - mf(v_2) + mf(x_2) - mf(y_2)$$

Then dividing both sides of the equation by the scale modulus m and eliminating the subscripts gives

$$\frac{p + q}{m} = f(u) - f(v) + f(x) - f(y) \quad \dots\dots\dots\dots \quad (2)$$

Thus, four variables written in the form of equation (2) may be applied to a special slide rule for the solution of one variable if the other three are known.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